EFFECT OF SHEAR STRAIN ACCELERATION ON MATERIAL PROPERTIES OF ALUMINIUM

by

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DEPARTMENT OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

AUGUST, 1989

EFFECT OF SHEAR STRAIN ACCELERATION ON MATERIAL PROPERTIES OF ALUMINIUM

A Thesis Submitted
In Partial Fulfilment of the Requirements
for the Degree of
MASTER OF TECHNOLOGY

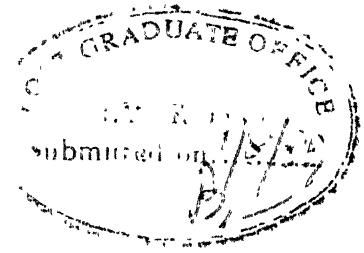
by
SANJAY KUMAR VERMA

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CERTIFICATE

This is to certify that the thesis entitled " **Effect of Shear Strain Acceleration on Material Properties of Aluminium**" by Sanjay Kumar Verma is a record of work carried out under our supervision and has not been submitted elsewhere for a degree.

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ABSTRACT

A technique to determine material property at high shear strain acceleration has been developed. A short thin tube specimen bonded between two Kolsky bars is subjected to a torsional pulse with a total durations of 700 μs. The far end of the incident bar is made tapered to generate the pulse with a rising ramp. The incident pulse is generated by storing torque in certain length of the incident bar and then suddenly releasing it with the help of quick release mechanism. The pulse is reflected partly from the specimen. The rest of the energy is transmitted to the transmitted bar. Reflected and transmitted pulses were recorded for analysis. The reflected pulse is proportional to shear strain rate and transmitted pulse is proportional to shear stress in the specimen.

The specimen of aluminium deforms without workhardening even at high strain rates. The material behaviour was found to depend on strain acceleration. The flow stress decreases as the strain acceleration is increased.

NOMENCLATURE

c	Shear wave speed
d	Dia. of rod
d_s	Dia. of specimen
e	Output voltage
e^c	Calibration output voltage
E	Applied voltage
γ	Shear strain
$\dot{\gamma}$	Shear strain rate
$\ddot{\gamma}$	Shear strain acceleration
$\dot{\gamma}^c$	Calibration shear strain rate
τ	Shear stress in bar
τ_s	Shear stress in specimen
τ^c	Calibration shear stress
ρ	Density
R	Resistance of strain gauge
R^c	Calibration resistance
t	Time
t_s	Specimen thickness
T	Torque
x	Distance

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION :

Plastic deformation of metal at low strain rate(less than Ø.1/sec.) is generally considered to be independent of rate of deformation. The plastic deformation is caused mainly by the slip mechanism such as generation and motion of dislocation and it is pertinent to express the deformation in terms of relation between shear strain and shear stress τ . The relationship between γ and τ usually obtained through an experiment in which pure torque is applied to a very thin wall tube and measuring the rotation of the tube. The relationship is well known and can be expressed as

$$\tau = f(\gamma)$$

In some metals like aluminium,copper,lead the effect of strain rate is quite pronounced specially at strain rate above 1ØØ/sec. The yield stress increases with increasing strain rate and workhardening behaviour is also found to be affected. It is generally believed that at higher strain rates, it becomes difficult for dislocation to multiply and move. However,it is still puzzling to find that some metals are not affected as far as constitutive relation is concerned. That is why,materials are characterized as strain rate sensitive and strain rate insensitive materials. Therefore in general,the flow stress is not only the function of strain but also depends on strain rate , i.e.

$$\tau = f(\gamma, \dot{\gamma})$$

In machining operations a thin strip of material is fractured out from the workpiece by the advancing tool tip and then it is being sheared in the shear zone at a very high strain

rate. When the material comes out the shear zone is called chip and its orientation is different from its original position so that it can conveniently slide over the rake face of the tool. The strain rate within the shear zone varies with cutting speed and is constant for a given cutting speed. But in certain machining operations when cutting speed varies;for example,facing and taper turning;and hence the shear strain rate varies, this introduces a new variable shear strain acceleration .Therefore a more general constitutive equation is

$$\tau = f(\gamma, \dot{\gamma}, \ddot{\gamma})$$

It is worthwhile to understand the effect of strain acceleration on flow stress. But the machining operation is quite complex and the extent of shear zone is hard to determine, especially ,during the chip formation. Rather it is desirable to setup a controlled experiment which directly determine the relation. One of the ways is to subject a thin tube to increasing torque to have varying shear strain .

1.2 LITERATURE SURVEY :

1.2.1 KOLSKY TECHNIQUE IN COMPRESSION AND TENSION :

Kolsky[1] was first to work on high strain rate testing in 1949. In his technique, a cylindrical specimen of short length is sandwiched between two long, hard and elastic bars of circular cross-section (known as Kolsky bars). The specimen is loaded in compression by passing a stress pulse generated by a detonator, which imparts velocity to the bars. Kolsky called it split-Hopkinson bar technique. This is now being increasingly known as Kolsky technique after its inventor.

In the Kolsky principle, a specimen is allowed to acquire a uniform stress but its opposite faces move in the same direction but at different velocities thereby compressing the specimen. The compression is made to occur at a high rate to obtain high strain rate by proper choice of length and diameter

of specimen and diameter and material of the Kolsky bars.

Davies and Hunter[2] (1963) setup the Kolsky experiment and studied its theory to define the limits of the technique. They adopted small specimen explosively loaded anvil bar as one of the Kolsky bars. Specimen were subjected to a loading cycle of 30 μsec. duration with a rise time of 10-15 μsec. They studied the strain rate behaviour of some metals like annealed copper, aluminium, magnesium and polymers.

Lindholm[3] (1964) conducted experiments on Kolsky pressure bar to determine the strain rate sensitivity of lead, aluminium and copper. The loading pulse was initiated by axial impact from a striker bar.

Hauser[4] (1966) developed a tension version of Kolsky pressure bar technique, which enabled him to find stress-strain behaviour of materials in tension at high strain rates. He allowed the compression pulse of a conventional technique to pass from one Kolsky bar to another through a tube specially designed to enclose the specimen. The compression pulse in the second Kolsky bar returned from its free end as a tensile pulse. This pulse no longer passed through the specimen as the tube was not bonded to the Kolsky bars.

The Kolsky pressure bar has following advantages and disadvantages.

(A) Advantages:-

(i)This is the first experimental technique to determine strain-stress diagram at different strain rates as high as 10^3/Sec. Most of the forming and machining operations are done in this order of strain rate.

(ii) Easy to Conduct.

(B) Disadvantages :-

(i) State of Stress is questionable due to lateral expansion of specimen. Due to lateral stresses frictional force acts

between the specimen and bar which complicates the problem.

(ii) Even a zero rise time pulse introduced at one end of the bar cannot propagate sharply. Its rise time increases with the increase in diameter.

1.2.2 KOLSKY TECHNIQUE IN TORSION :

The experiment is designed to have zero friction at both the interface by careful polishing and lubricating the surfaces. However,frictional force is observed to act in most cases. Since the extent of the frictional force and the associated stress components cannot be measured or assessed easily,the true state of stress is not known.Baker and Yew [5] (1966)conducted torsion experiments at slow and high strain rates on aluminium alloy, copper and on low,medium and high carbon steels.

For higher rate of loading, a cylindrical copper specimen was silver brazed between two steel tubes. One end of the long steel tube was firmly clamped in the chuck of the lathe, and the middle section of it was fixed by a clamp. Torsional strain energy was stored in the loading rod by turning the lathe head through an angle and locking it at that position with the back gear of the lathe. A torsional strain pulse was generated by sudden release of the pre-twisted loading rod.

Duffy, Campbell,Hawley [6] (1971) conducted experiments on 1100-0 aluminium. Thin tube specimens with integral flanges were used. The torsional impact was applied by explosion. The incident torsional pulse was first smoothened before transmitting through specimen.

Duffy, Hawley and Frantz[7] conducted experiments on lead specimen. A tubular specimen was cemented between two long bars. A torsional pulse was imparted at one end by two explosions which are detonated simultaneously . The pulses are smoothened before passing through the specimen.

1.2.3 STRAIN ACCELERATION IN MACHINING :

As stated earlier, when the cutting speed during machining varies, it results in shear strain acceleration. Jain proposed a model that shear strain acceleration has a significant affect on shear flow stress.

Experimental work of Kumar[8] on shear strain acceleration reveals that the material yields at lower flow stress, at a certain strain rate level if higher strain acceleration is used. It means the shear flow stress reduces at higher shear strain rate acceleration. Kumar reasoned that at a certain strain rate achieved through a high strain acceleration, the dislocation interaction may not occur (due to lack of time), to the extent it would have been at that strain rate attained in the normal way. Also, phenomena like jog-formation may be inhibited or at least reduced. This would lead to lower deformation forces and hence a lower shear flow stress.

1.3 HIGH STRAIN RATE SHEAR TEST :

Shear deformation is the primary deformation mode encountered in application such as machining,punching, grinding and forming operations and in events or processes that result in penetration. To accurately predict material behaviour in these operations, it is necessary to test the material in pure shear at different shear strain rates. Although the results obtained from tension or compression can be converted to shear stress and shear strains with the help of flow rules (von Miser or Tresca), the conversion seldom extends into a high strain range (more than 20%). The results obtained from axial test provide higher values on flow stress than shear tests.

ADVANTAGES OF TORSION TEST :

(i) Shear eliminates the problem of necking, which occurs in tension test.

(ii) It eliminates the problem of barreling, which occurs in compression testing.

(iii) No radial stress or frictional force between specimen and bars that occurs in axial test.

(iv) Torsional pulses move in its primary mode and all frequency components have the same velocity and hence the torsional pulse do not change its shape as it propagates towards the specimen, whereas in axial test the pulse traveling down the bar undergoes geometric dispersion, because the different frequency components in the axial pulse have different velocities.

(v) Due to absence of geometric dispersion torsional pulse maintains its rise-time until it reaches the specimen, independent of length of travel. Therefore the torsional strain gage station can be located as near or as far from the specimen as desired. Whereas in axial test, a gage placed too close to the specimen is subjected to three dimensional end effects, while a gage placed too far from the specimen produces unsatisfactory result because of geometric dispersion.

(vi) Torsion tests can be conducted to study the effect of temperature on flow stress.

DISADVANTAGES OF TORSION TEST :

(i) If a torsional pulse is noisy when initiated (i.e. if some high frequency components are superimposed on the main pulse), this characteristic will be maintained regardless of the length of the bar.

(ii) Gripping, the slow tubular specimen is difficult, and special care must be taken that the specimen are held firmly in the bar and that there are no reflections due to the gripping method.

Different method of high strain rate shear test is devised to

work at different strain rate level. These methods are :

(i) High speed Hydraulic torsional machines

(ii) Torsional Impact Testing

(iii) Torsional Kolsky bar

(iv) Double-notch shear and punch

(v) Pressure-shear plate Impact

A servohydraulic machine is most convenient method for rates up to 1Ø /Sec. Torsional impact loading has been widely used to obtain strain rates up to above 1ØØ /Sec. Between strain rates $1Ø^2$ to $1Ø^4$/Sec the torsional Kolsky bar has proved to be a convenient method of testing. Double shear and punching provide somewhat higher strain rate than the torsional Kolsky bar. For rates above $1Ø^4$/Sec up to about $1Ø^7$/Sec, a plate impact test is used to subject thin specimens to combined pressure and shear.

1.4 THIS STUDY :

In the present work it is tried to modify the existing, stored torque torsional Kolsky bar, which is capable to generate square input pulse which causes deformation of material at a constant strain rate. Different modification to the existing setup is done to get a ramp input pulse which causes the deformation of specimen at varying strain rate and hence at some strain acceleration. The most suitable modification is chosen for the final experimentation. The experiments are conducted on aluminium.

The thesis is organized as follows.

(i) Experimental technique and related theory is described in chapter 2.

(ii) Experimental results one discussed in chapter 3.

(iii) Concluding remarks are given in chapter 4.

CHAPTER - 2

EXPERIMENTAL TECHNIQUES

A conventional Kolsky set-up in torsion generates a constant amplitude torque loading pulse that causes the plastic flow at constant strain rate for most of the metal specimens. In order to have the increasing strain rate (strain acceleration) the apparatus has been modified to generate a ramp incident pulse. Since the Kolsky technique is not known to many persons, details of the conventional technique are presented first. The description on the modification made in the study follows.

2.1 CONVENTIONAL TORSIONAL KOLSKY APPARATUS :

Kolsky principle is schematically shown in Fig (2.1).A thin tube specimen is bonded between bars . The specimen used in torsional Kolsky bar experiments usually are thin - walled tubes with integral flanges machined from bar stock. In materials that have a relatively low flow stress, aluminium, OFHC copper or zinc, for example, the specimen can be held in position by cementing its flanges to the Kolsky bar with an epoxy cement. This provides sufficient strength and a rigid connection. Specimen geometry is an important consideration for the success of the experiment. The flanges are bounded to the ends of incident and transmitted bars. The cross-section of the flanges is designed carefully such that the thin tubular specimen fails before the bonds. Also, when compared with the specimen the stiffness of the flanges has to be much larger to make their rotational deformation negligible.

The bars are made of aluminium alloys between which a specimen is bonded. Each bar is supported along its length and aligned properly by a series of teflon bearings that

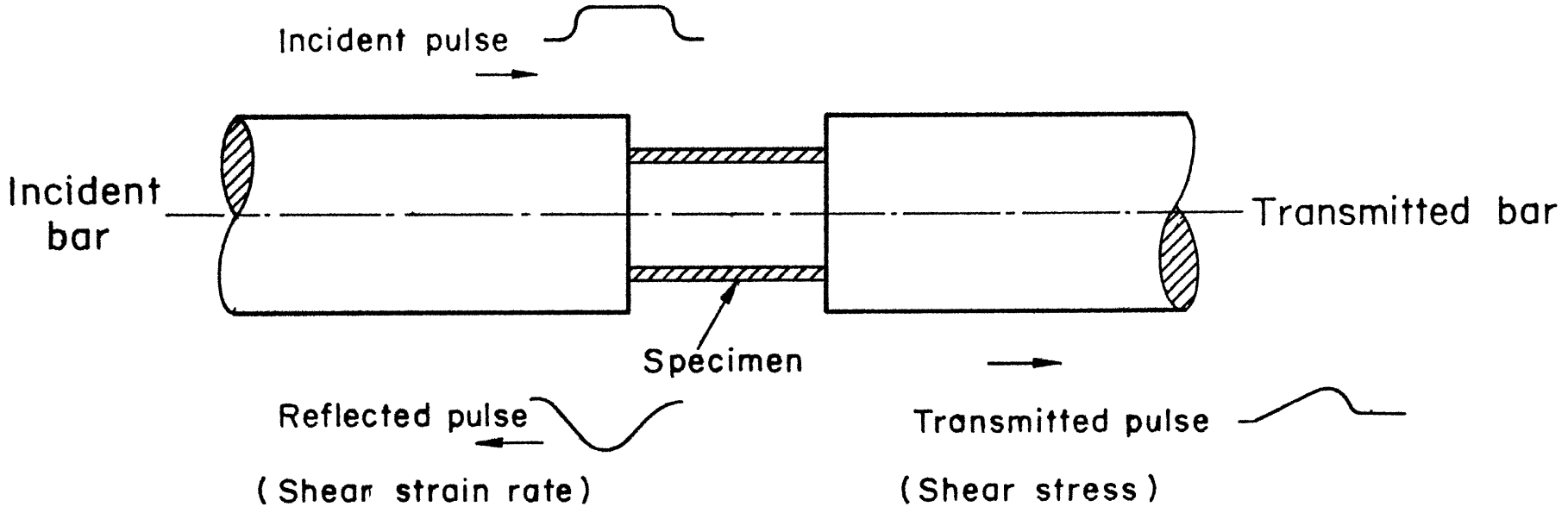


Fig.2.1 Kolsky principle

allow the bar to rotate freely in either direction. The bar to which the load is applied is called incident bar and the bar to which loading pulse comes after passing through specimen in called transmitted bar.

The loading pulse is produced by the sudden release of a stored torque. This requires a torque pulley at the end of the bar and a clamp positioned within a short distance to prevent rotation. The design of the quick release clamp has a direct influence on the rise time of the incident loading wave. In an ideal case the incident pulse should rise instantly to a constant amplitude and then drop-off immediately to zero at the end of the pulse. Thus forming a square loading pulse and providing deformation at a constant strain rate. In practice, a finite time is required to achieve maximum torque for most of the metals in the loading pulse. The rise time primarily depends on how fast the clamp opens. Two jaws with hinged bottoms press against the sides of the incident bar under the action of the V-notched bolt. Also soft brass spacers are placed between the bars and the jaws to avoid yielding at the contact points . To initiate the pulse, the bolt is tightened until it fractures. The amount of torque required to achieve the desired strain rate is a determining factor in selecting the notched pin material and the depth of notch. Pulse rise time is also affected by the choice of material for the notched pin. The pin material must exhibit minimal ductility, but must not be so brittle as to fracture before the clamp is tight enough to hold the desired stored torque. The desired clamping force and fracture point are achieved by varying the depth of notch.

Releasing the clamp is like bursting a dam,the stored torsional pulse moves towards the specimen as shown by step by step in the fig.(2.2). A torque of constant amplitude equal to half of the stored torque, propagates down the bar toward the specimen. Simultaneously an unloading pulse of equal magnitude propagates from the clamp toward the torque pulley.

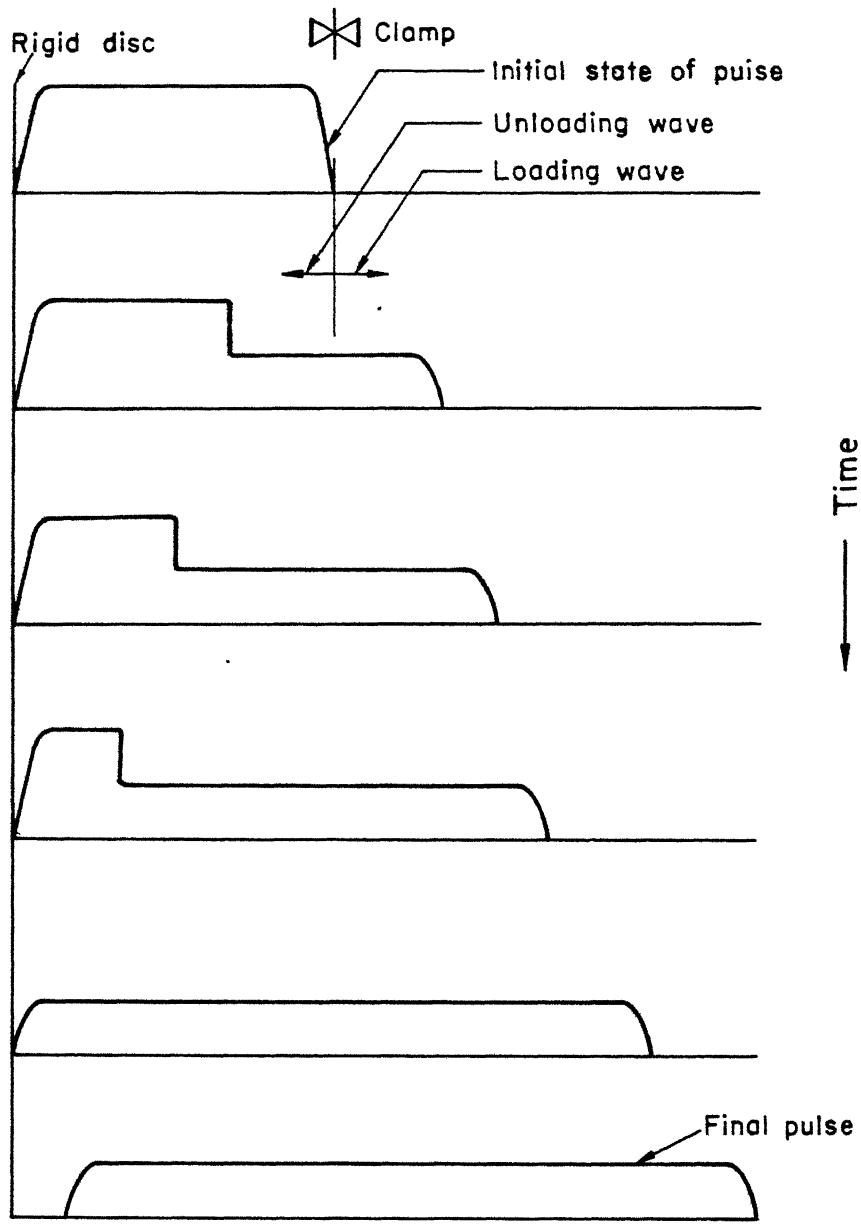
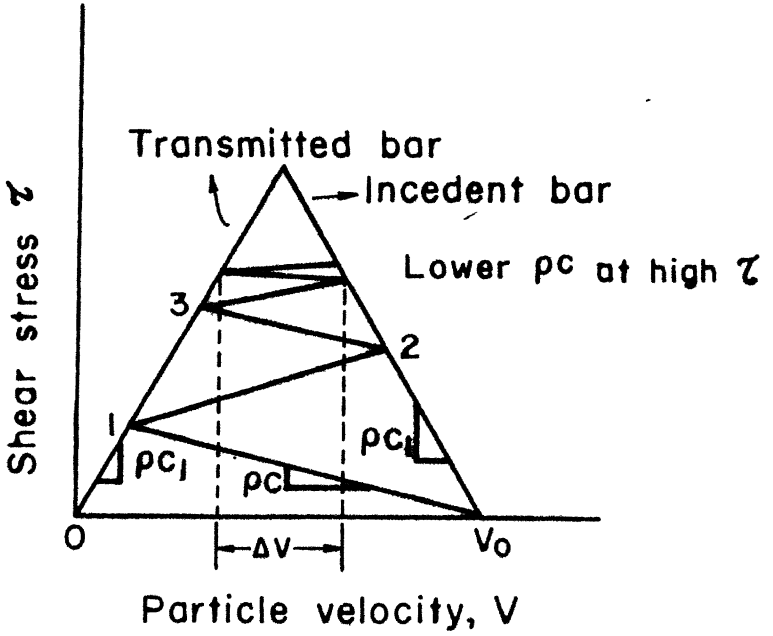


Fig.2.2 Step by step illustration of pulse from stored torque

The torsional mechanical impedance of the pulley is sufficiently large that after reflection the unloading wave reduces the torque in the incident bar to zero as it propagates back along the bar generating a constant amplitude pulse. The duration of the loading pulse is the time required for the pulse to travel twice the distance along the bar between the clamp and the torque pulley.

As the pulse travels down the bar it is detected by two four-arm electric resistance gage bridge mounted at 45° to the axis of the bar at equal distance from the specimen . The gages are placed at a sufficient distance from the specimen so that a clear record of both the incident and the reflected pulse is obtained without overlap or interference. The distances are decided on the basis of shear wave speed which is nearly 3.1 mm/μs for aluminium bar. To ensure that the reflected pulse does not overlap with the incident pulse at a gage station, the gages must be placed from the specimen, atleast at a distance equal to that between torque pulley and the gage station. But to ensure that the stress in the bar returns to zero after the pulse has passed, the gages should be located at an even greater distance from the specimen. A similar strain gage bridge for monitoring the transmitted pulse is located at the same distance from the specimen as the incident gage. The signals are recorded on a digital storage oscilloscope of sufficiently high frequency(1 MHz) response. Noise in the incident, reflected and transmitted pulse are suppressed by the use of coaxial cables and B&C connection.

The use of short specimens in the torsional Kolsky bar implies that a nearly uniform state of stress is obtained after a few reverberations of the loading pulse in the specimen. How the strain rate becomes constant after a few reverberations is shown in Fig.(2.3) of stress - particle velocity diagram. When the pulse from incident bar comes to the specimen, its state of stress is 1. Then it passes through the specimen and comes at the transmitted bar end where its state of stress is 2; it



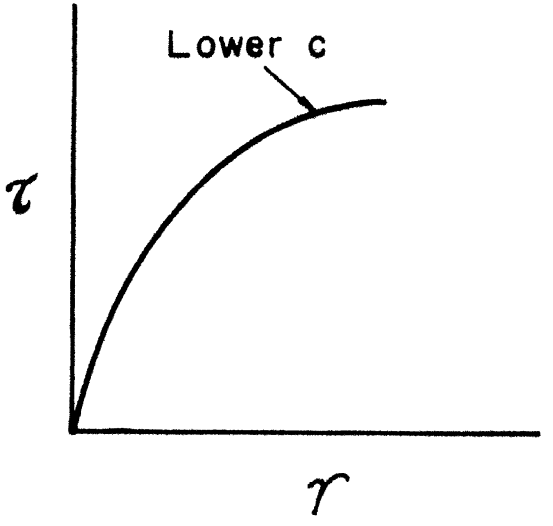


Fig. 2.3 Reverberations of pulse inside the specimen

reflects from this end and comes to incident bar side where its state of stress becomes 3. After two three back and forth reflections the stress level goes up sufficiently high to yield the material. As shown in the stress - strain diagram, the slope of curve comes down and hence the value of c(shear speed). This results in reverberation of pulse at nearly constant stress level. The value of δv gives strain rate which becomes constant after yielding.

A torsional pulse, known as incident pulse, is made to enter the specimen tube. Part of the energy is reflected and is recorded as reflected pulse in the incident bar. The rest goes through to the specimen and is knows as transmitted bars. The one dimensional wave theory is used to process the data. It is exact for circular cross-section consequently, because (i) there is no warping, (ii) State of stress remains one dimensional all the time and (iii) stress pulse does not change shape as it travels in the bars. The results are simple; the transmitted pulse is proportional to the shear stress in the specimen whereas the reflected pulse is proportional to the strain rate. For finding the strain, the strain rate is integrated after making the obvious assumption that strain was zero at the beginning of the experiment.

In Ref.(9) the experiments were done on the aluminium alloy using a square input pulse. A typical record of incident, reflected and transmitted pulses are shown in the fig.(2.4). The strain rate was constant in each experiment. The experiments were conducted at 17Ø, 26Ø and 27Ø S^{-1}. The shear stress - strain diagram for different strain rates are shown in Fig.(2.5).The shear stress - strain relations show very little workhardening.

2.2 MODIFICATIONS TO THE EXISTING SETUP :

Various modifications were tried to get a smooth ramp input pulse are as follows.

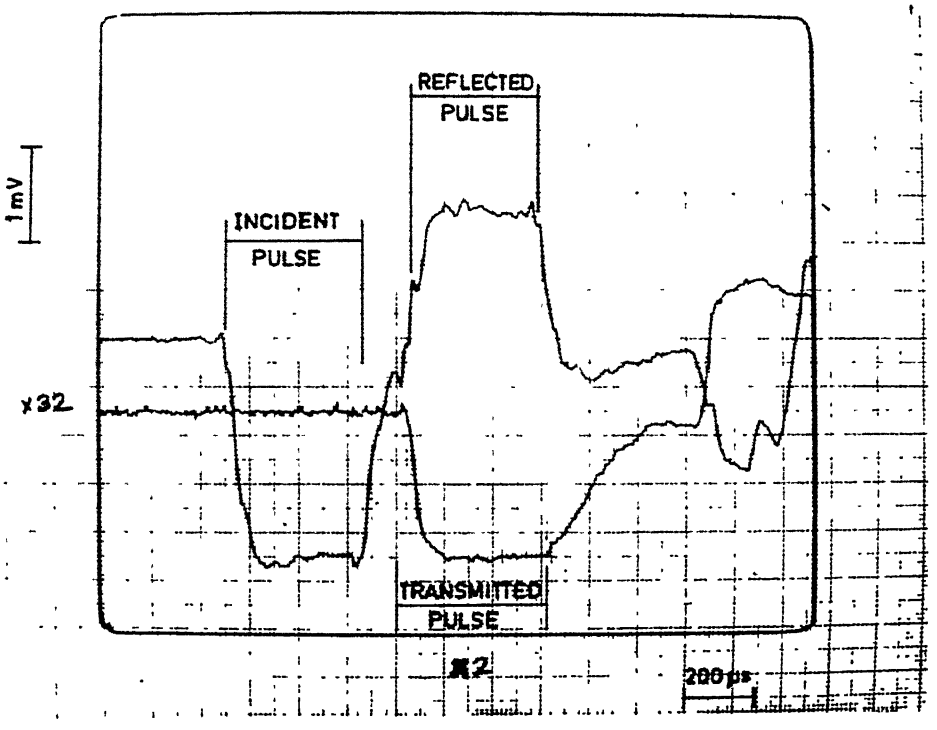


Fig. 2.4 Oscilloscope record of incident, reflected and transmitted pulses of aluminium alloy specimen (Expt. 85-15)

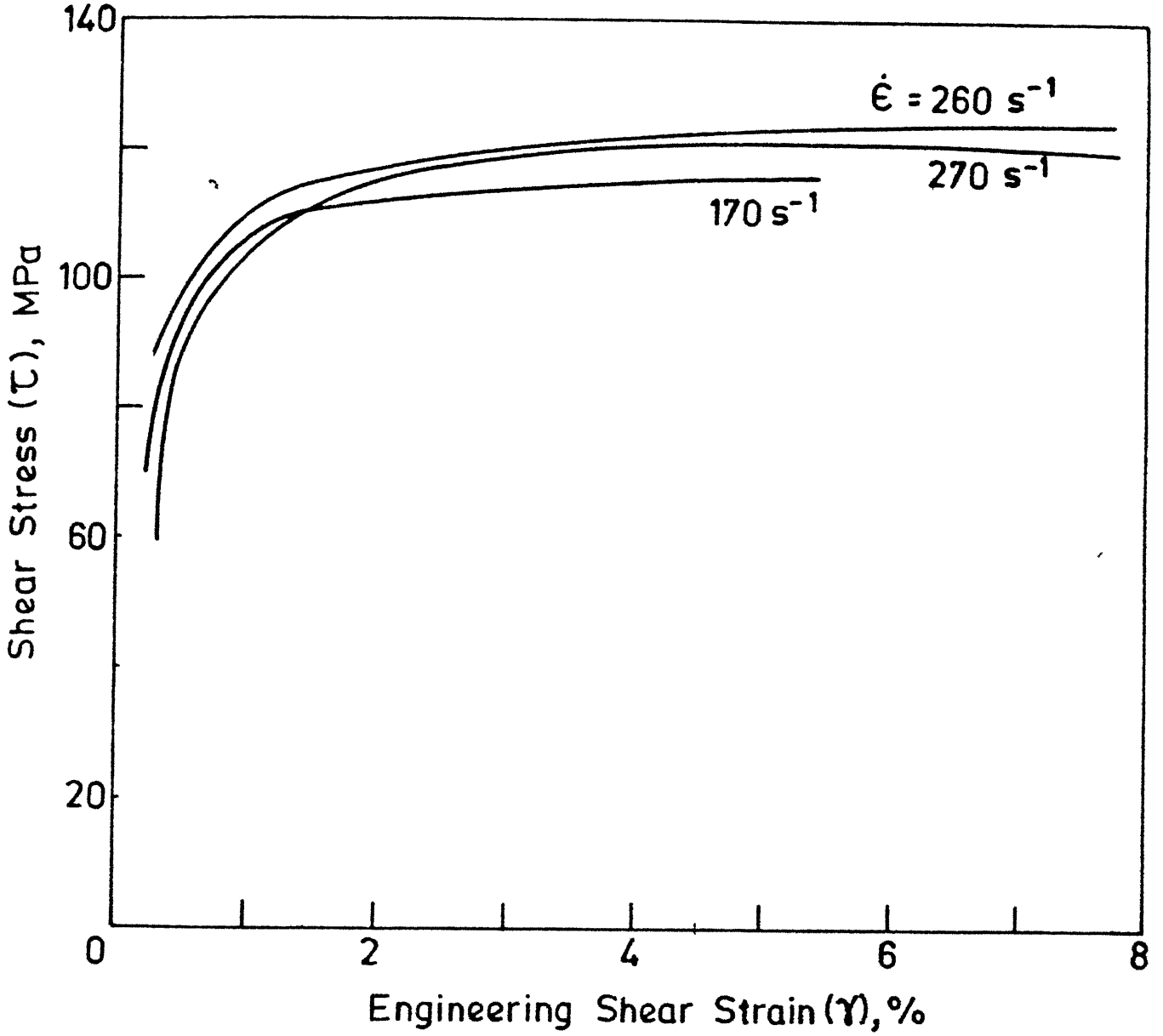


Fig. 2.5 Dynamic shear stress - shear strain curves of aluminium alloy.

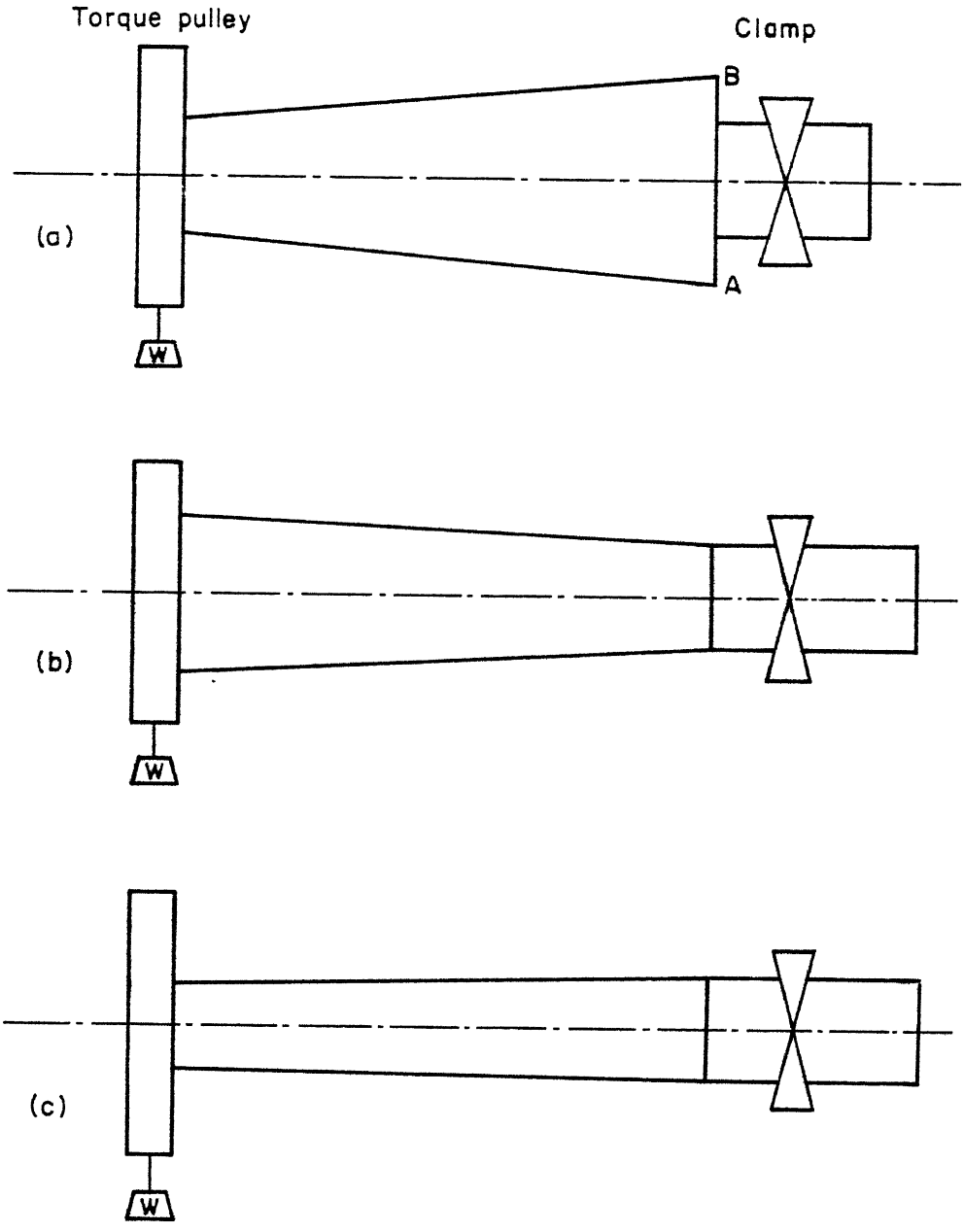


Fig. 2.6 Various modification

(i) A Steep taper decreasing towards the torque pulley as shown in Fig.2.6(a).
(ii) A Steep taper increasing towards the torque pulley as shown in Fig. 2.6(b).
(iii) Controlled release of torque by modifying the clamp jaw.
(iv) Smooth taper decreasing towards to torque pulley with initial diameter equal to that of incident bar as shown in fig.2.6(c).

Reasons for not working of first three modifications :

The first modification did not work because the diameter AB of taper portion were much larger than that of the incident bar under clamp, this resulted in reflection of loading pulse from the face AB.

The second modification did not work because the incident pulse had unloading portion more dominant than loading portion. The loading ramp was steep and depends mainly on the clamp rise time, unloading lamp was controlled and smooth but was not useful due to elastic recovery and Baushinger's effect.

In the third modification the Jaw was designed to give a large rise time. It was achieved by making it less stiff, heavy and long. But the ramp obtained was not smooth and showed some kinks which gave highly fluctuating strain rate.

The last modification (a smooth taper) shown in Fig.2.6 (c) was adopted for final experimentation because it provides smooth rising ramp and also a smooth linear reflected pulse for the strain rate.

2.3 DESCRIPTION OF THE EXPERIMENTAL SET-UP :

A stored torque Kolsky bar is shown schematically in the Fig (2.7). An input pulse is applied to the thin tube specimen with integral flange, held between two long aluminium bar. Both the

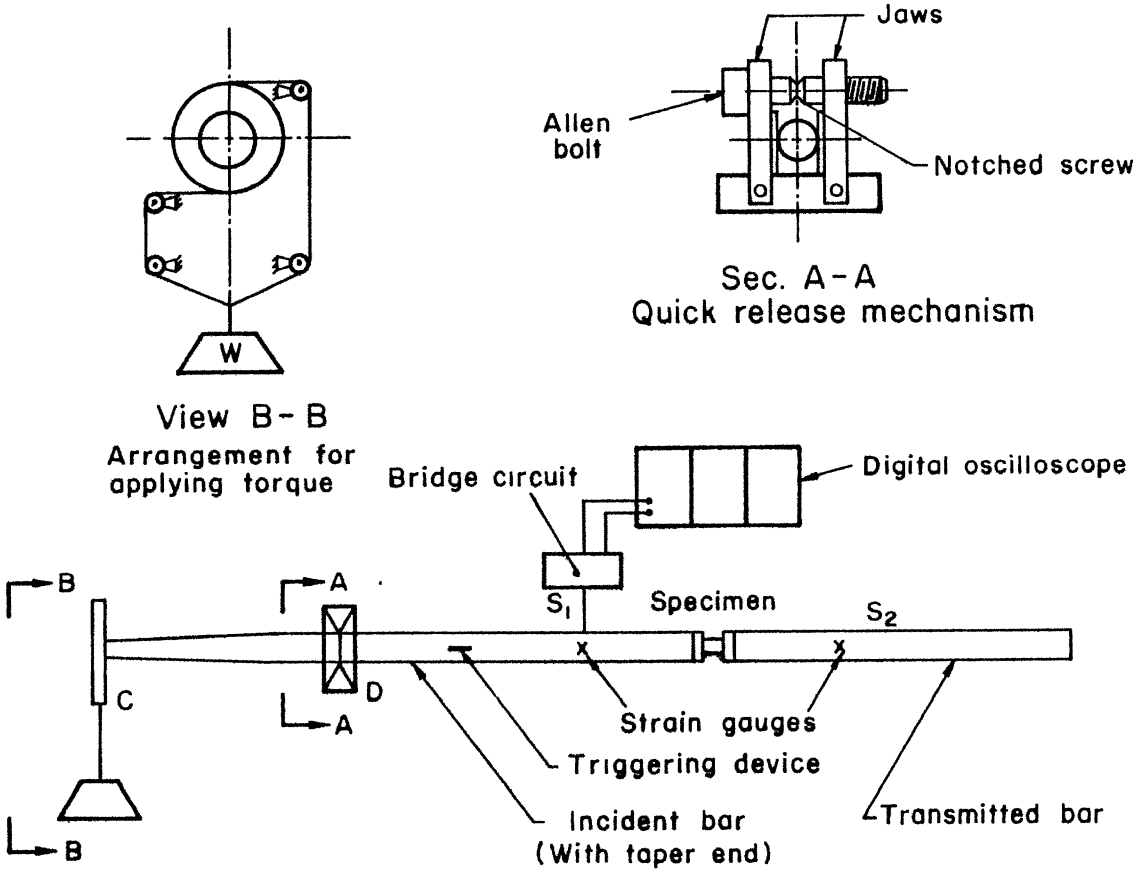


Fig.2.7 Schematic diagram of Kolsky torsional Machine

incident and transmitted are of 25 mm dia and 2.12m and 2.14m length respectively. The incident bar has a taper in certain length at the far end from the specimen. The bars are supported by a series of teflon bearings that allow the bar to rotate freely in either direction. The ends of the bar to which specimen is bounded are machined flat and normal to the axes of the bar.

The loading pulse is produced by the release of stored torque. The torque is stored in the incident bar with the help of torque pulley and a clamp with quick release mechanism. The clamp prevents rotation of the portion of incident bar between clamp and pulley when the torque is applied.

Once the incident bar is clamped by the jaws of the quick release mechanism, a pure torque is applied at the end of bar. Two steel wires wrap around a large diameter disk (view B-B, of fig (2.7), which are pulled by uniform tension developed through dead weights. The top and bottom steel wires are set horizontal to eliminate binding load on the incident bar. The magnitude of the torsional pulse is regulated by varying the dead weights and the duration of pulse is regulated by choosing an appropriate length between the load disk and the clamp (distance CD in Fig.(2.7). In fact duration of pulse is equal to 2 CD/c where c is the shear wave speed.

To bond the specimen between the two Kolsky bars, a light pressure should be applied on the Kolsky bars specimen assembly. Pressure should not be so high that it yields the thin tubular specimen. A device is designed and fabricated which applies pressure at the far end of the transmitted bar Fig.(2.8). The incident bar is clamped at one of its supports and all the three components are aligned in a straight line. The screw of the pressure application mechanism is rotated. The rubber pad avoids application of large loads on the thin wall of the specimen.

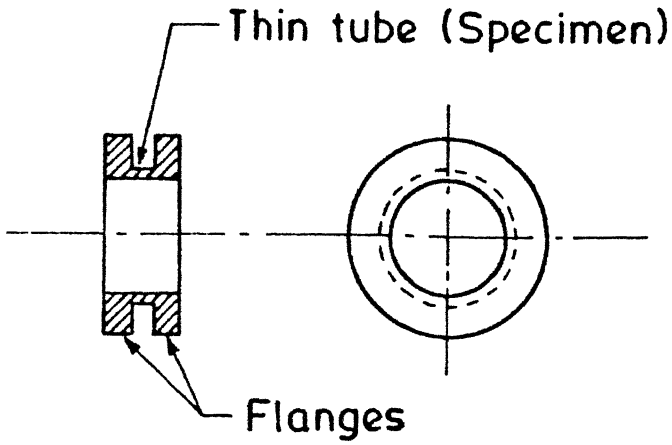
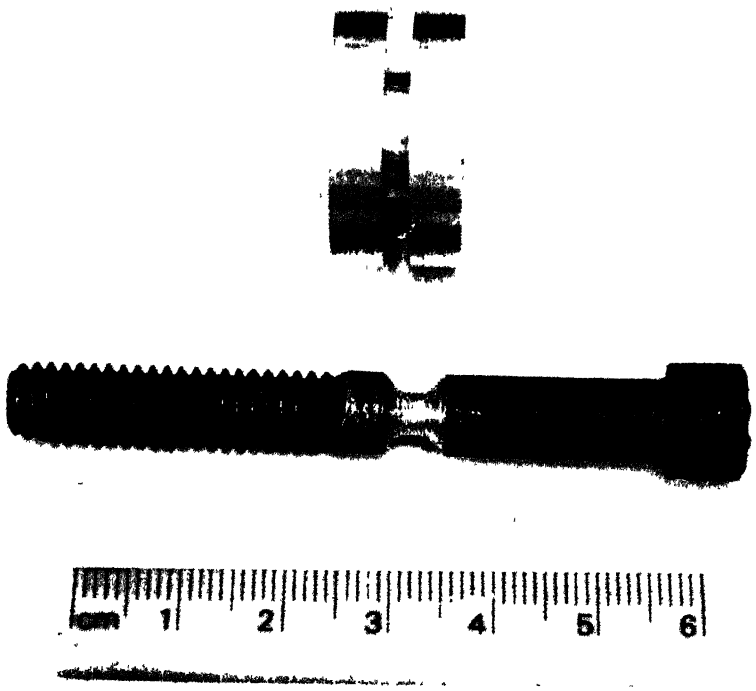
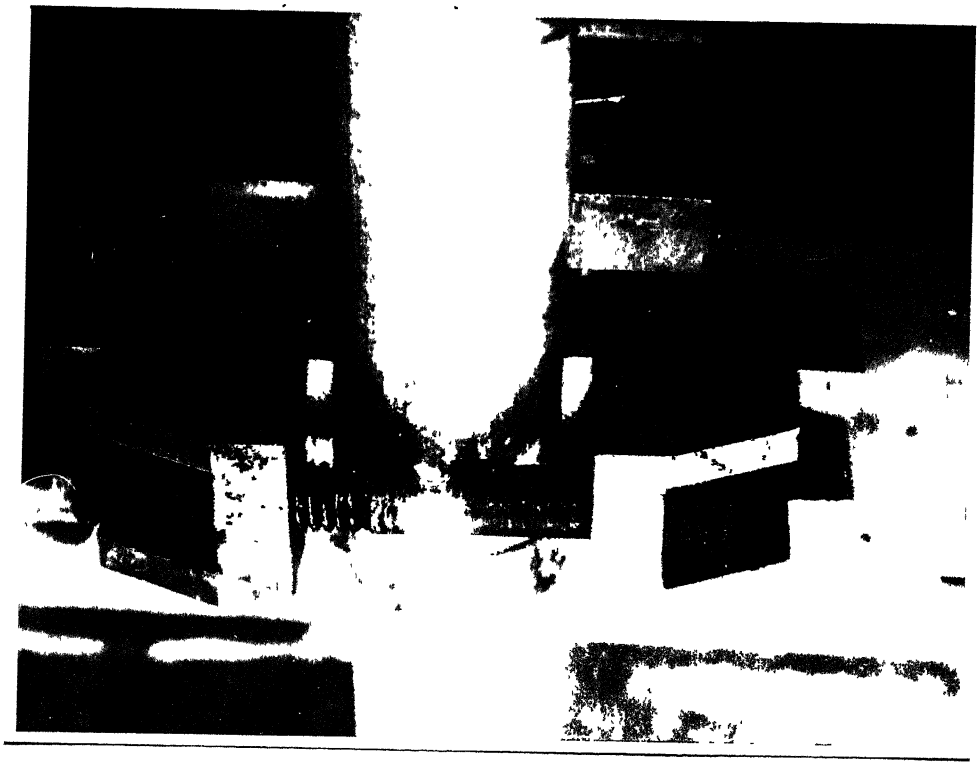


Fig. 2 10 A typical tubular specimen.

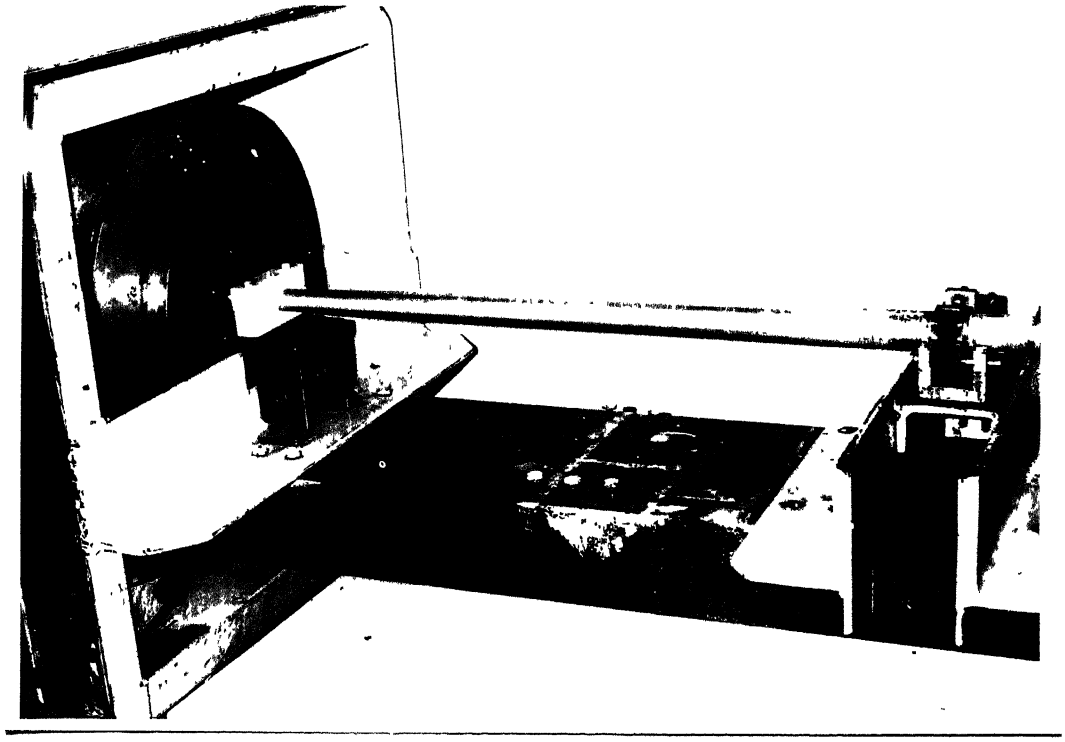




SPECIMEN BONDED BETWEEN BARS



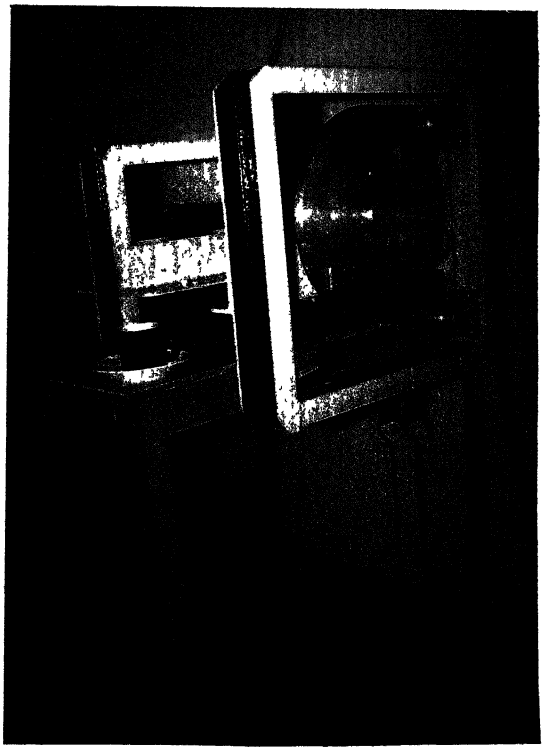
QUICK RELEASE MECHANISM



TAPER PORTION OF INCIDENT BAR



OVERALL VIEW OF THE SET-UP



LOADING ARRANGEMENT

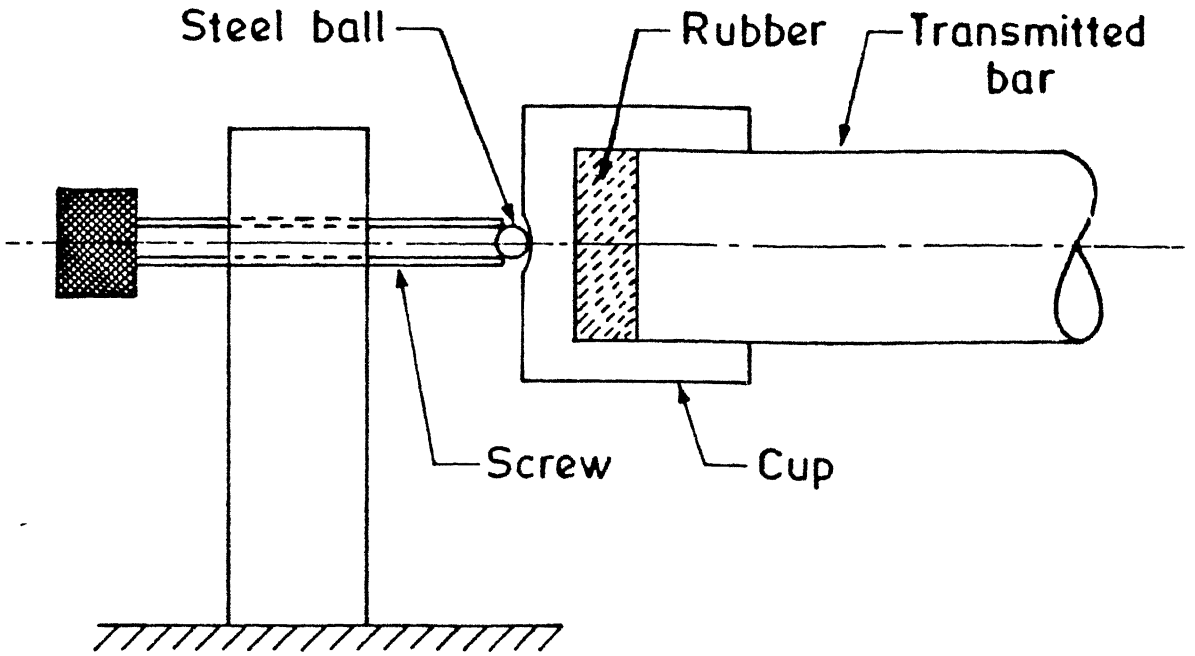


Fig.2.8(a) Schematic diagram of load application arrangement during curing.

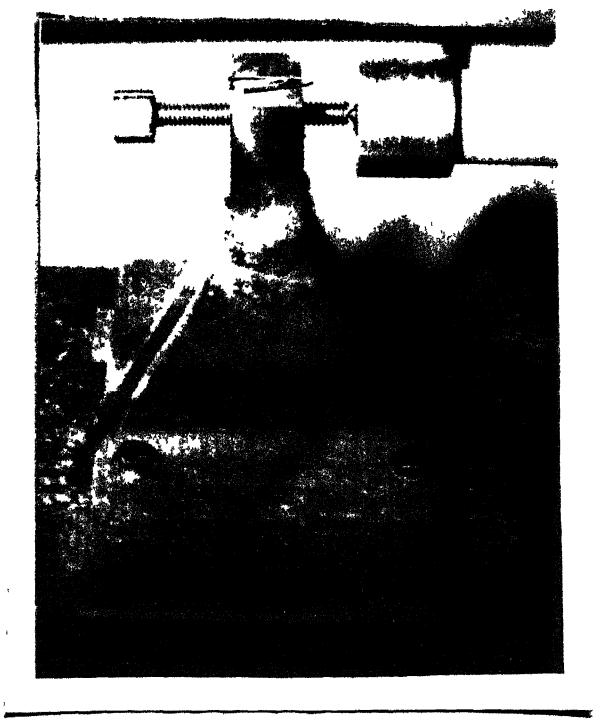


Fig.2.8(b) Hardware of the arrangement.

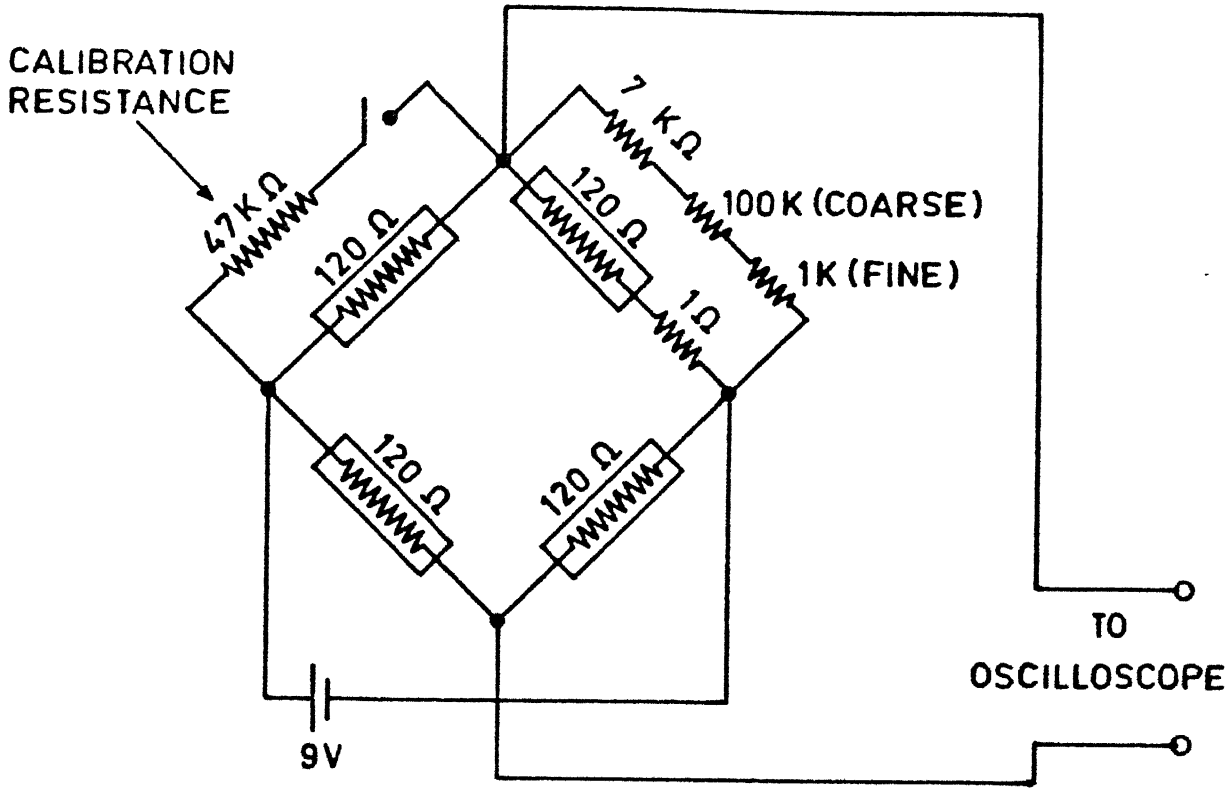


Fig. 2-9 Bridge circuit using 45° strain gauges (four active arms)

In the Kolsky Technique, the correct size of a specimen is determined by trial and error. The length and thickness of the tubular specimen are chosen on the basis of preliminary results on specimen prepared by guessing the sizes. A short length specimen make the stress uniform in the specimen in a short time but provides low strain rates. A long specimen is deformed at high strain rate but it may not be desirable. It takes a long time for the stress wave to transverse the length of the specimen. As a result, uniform stress is not obtained until 3 to 4 reverberations of stress wave front takes place inside the specimen. By the time uniform stress is attained, the major part of the stress wave is consumed and we do not obtain stress-strain curve for a considerable range of strain. Thus the length of the specimen has to be chosen carefully by a series of a preliminary experiments.

To record torsional pulses rosette strain gauges are mounted on the incident and transmitted bars at a distance of 1m from the specimen end in each bar. At a location two set of rosette strain gauges mounted diagonally opposite to each other are used, thus providing four active arms of the wheat stone bridge. The signals are of very low magnitude, therefore, the Kolsky bar are made of aluminium which provide three times more strains in bars made of steel.

The schematic diagram of the bridge circuit is shown in Fig. (2.9), which makes use of 120 ohms BLH rosette strain gauges of gage factor 2. A resistance of about 47 Kilo-ohm is used parallel to one of the arms to calibrate the circuit. In order to balance the circuit a small resistance of 1 ohm is placed in series to one of the three remaining strain gauges as shown in the figure. A set of three resistances connected in series are placed parallel to the strain gauge: one of them is a fixed resistance of 7 k ohm and the other two are variable resistance of 100 Kilo-ohm and 1 k ohm for coarse and fine control respectively.

A digital oscilloscope (NICOLET MODEL NO.2Ø9Ø II) is triggered by a phonograph needle placed between the strain gauge and the quick opening mechanism. The released torsional pulse triggers the oscilloscope before the pulse reach the strain gauge . The response time of the needle is erratic but does not cause problem because the memory of the digital oscilloscope retains even those information which are supplied before the triggering occurs.

The torque is stored in the portion of CD of the incident bar. The length CD was decided by some trial run to assure distinct record of incident and reflected pulse on the same channel of oscilloscope.

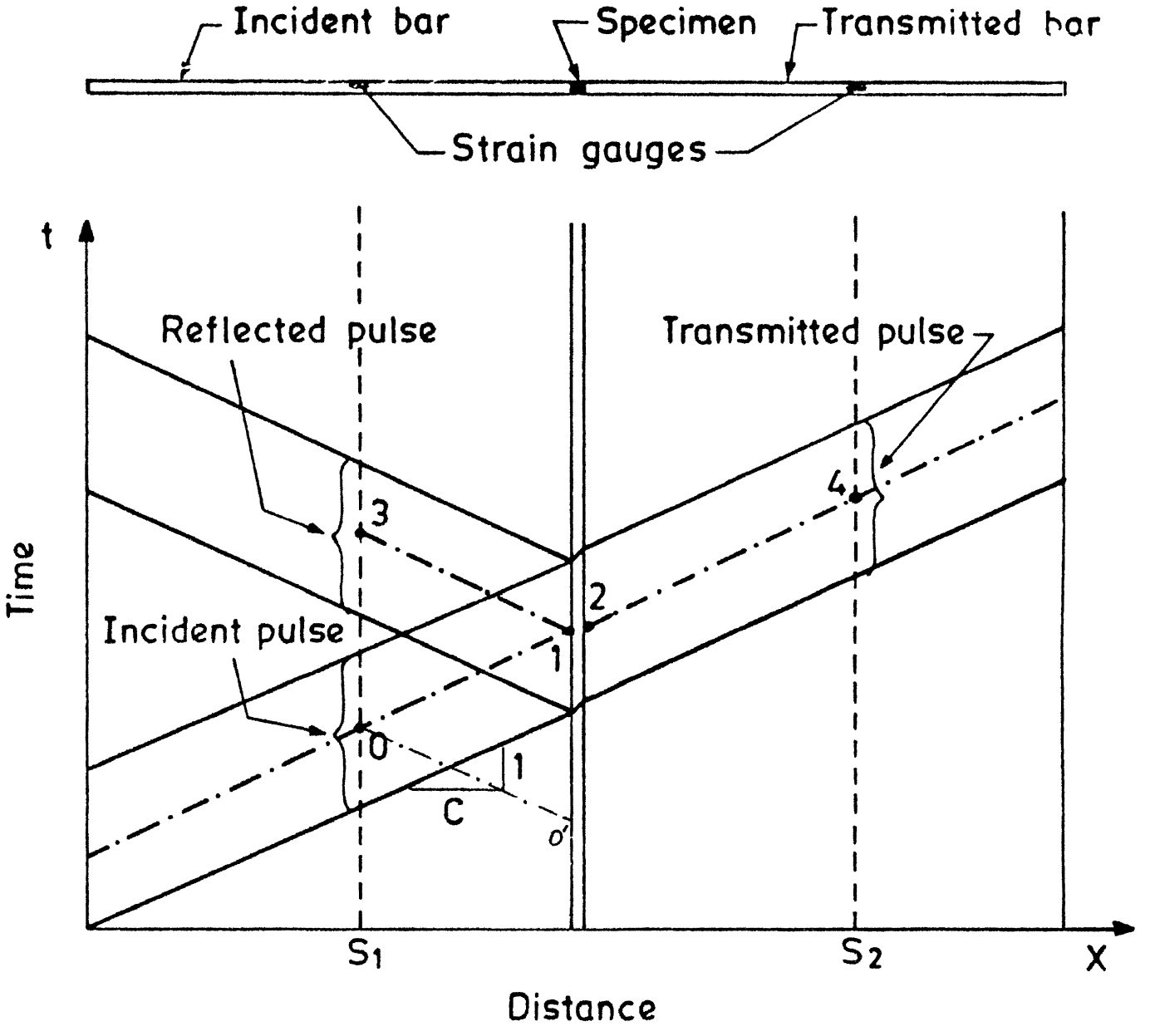


Fig.2.11 Time - distance (t - x) diagram.

2.4 THEORETICAL ANALYSIS

A typical record of all the three pulses, incident, transmitted, reflected are shown in fig.(2.4). The reflected pulse is proportional to shear strain rate and the transmitted pulse is proportional to the shear stress in the specimen. The proof is based on one dimensional wave propagation theory Ref.(9)

considering the Time-Distance graph of fig.2.11

One dimensional wave equation along the characteristics with the acoustic impedance ρc is expressed by

$$d\tau - \rho c dv = 0 \quad \text{(Along +ve characteristic)}$$

$$d\tau + \rho c dv = 0 \quad \text{(Along -ve characteristic)}$$

Using above relationship for evaluating state of stress at point 1

$$\tau_1 - \rho c v_1 = \tau_0 - \rho c v_0 \quad \text{---------- (1)}$$

Along OO'

$$\tau_0 + \rho c v_0 = 0$$

or $$\tau_0 = -\rho c v_0 \quad \text{---------- (2)}$$

substituting Eq.2 in Eq.1

$$\tau_1 - \rho c v_1 = 2\tau_0 \quad \text{---------- (3)}$$

similarly ,

$$\tau_1 + \rho c v_1 = 2\tau_3 \quad \text{---------- (4)}$$

Eq.3 & 4 give

$$\tau_1 = \tau_3 + \tau_\emptyset \qquad \text{---------- (5)}$$

$$v_1 = (\tau_3 - \tau_\emptyset)/\rho c \qquad \text{---------- (6)}$$

Also at point 2

$$\tau_2 + \rho c v_2 = \emptyset$$

$$\tau_2 - \rho c v_2 = \tau_4 - \rho c v_4 = 2\tau_4$$

These equations gives

$$\tau_2 = \tau_4 \qquad \text{---------- (7)}$$

$$v_2 = -\tau_2/\rho c = -\tau_4/\rho c \qquad \text{---------- (8)}$$

Since stress in the specimen (τ_s) assumed uniform after three four reverberations of the stress wave front within the specimen i.e.

$$\tau_s = \tau_2 = \tau_1 \qquad \text{---------- (9)}$$

From Eq.7 & 9

$$\tau_s = \tau_4$$

Thus the transmitted pulse provides state of stress in the specimen.

Strain rate can be given by

$$\dot{\gamma} = (v_1 - v_2).d_s/l_s.d$$

The factor d_s/d accounts for the difference in the diameters of the specimen and Kolsky bars.

Substituting the value of v_1 and v_2 in the Eq.1Ø

$$\dot{\gamma} = \frac{\tau_3 - \tau_\emptyset + \tau_2}{\rho c l_s} \cdot \frac{d_s}{d} \quad \text{----- (11)}$$

Using Eq.3 & 9

$$= \frac{2\,\tau_3}{\rho c l_s} \cdot \frac{d_s}{d} \quad \text{---------- (12)}$$

Thus the reflected pulse gives the proportional value of shear strain rate.

Based on the simple theory of circular bars shear stress(τ_s) in a thin cylindrical specimen is given as

$$\tau_s = \frac{2\,T}{\pi\, t_s(d_s^2 + t_s^2/3)} \quad \text{---------- (13)}$$

For the case of thin tube , $t_s^2/3$ can be neglected in comparison to d_s^2.

$$\tau_s = \frac{2T}{\pi . d_s^2 . t_s} \quad \text{---------- (14)}$$

Voltage output e_2 generated by all four strain gages of the bridge circuit shown in fig. is given by Ref.()

$$\frac{e_2}{E_2} = \frac{R_1 . R_2}{(R_1+R_2)^2} \left[\frac{\delta R_1}{R_1} - \frac{\delta R_2}{R_2} + \frac{\delta R_3}{R_3} - \frac{\delta R_4}{R_4} \right]$$

---------- (15)

For the case of identical arm of the bridge circuit

$$\frac{e_2}{E_2} = \frac{R^2}{(2R)^2} \cdot \frac{4\,\delta R}{R}$$

$$= \frac{\delta R}{R} \quad \text{---------- (16)}$$

By the definition of gage factor

$$F_2 = (\delta R/R)/\epsilon$$

$$\epsilon = \frac{e_2}{F_2.E_2} \qquad \text{---------- (17)}$$

The shear strain becomes

$$\gamma = \epsilon$$

and the Shear stress τ_2 in the transmitted bar is expressed by

$$\tau_2 = G = \frac{G\ e_2}{F_2.E_2} \qquad \text{---------- (18)}$$

The torque becomes

$$T_2 = \frac{\pi\ d^3}{16}.\tau_2 \qquad \text{---------- (19)}$$

$$T2 = \frac{\pi\ G\ d^3}{16}.\frac{e_2}{F_2\ E_2} \qquad \text{---------- (2Ø)}$$

Finally to obtain stress in specimen, substituting Eq.(2Ø) in Eq.(14)

$$\tau_s = \frac{G\ d^3}{8\ t_s\ d_s^2}.\frac{e_2}{F_2\ E_2} \qquad \text{---------- (21)}$$

For calculating the bridge circuit, resistance of only one is changed by placing a shunt resistance R_1. The calibration output e_2^c is obtained from Eq.(15)

$$\frac{e_2^c}{E_2} = \frac{\delta R}{4(R+R_c)}$$

This modifies Eq.(21) to give calibration output recorded on oscilloscope to τ_s^c expressed by

$$\tau_s^c = \frac{G\ d^3}{8t_s d_s^2 F_2}.\frac{R}{2(R+R_c)} \qquad \text{------- (22)}$$

To evaluate shear strain rate from Eq.(12) τ_3 is expressed by

$$\tau_3 = \frac{2Ge_1}{F_1E_1}$$

Which yields

$$\dot{\gamma} = \frac{2}{cl_s} \cdot \frac{d_s}{d} \cdot \frac{2Ge_1}{F_1E_1}$$

Where subscript 1 refers to reflected pulse recorded in the incident bar.

Putting $G = \rho c^2$ in above Eq.

$$\dot{\gamma} = \frac{2c}{l_s} \cdot \frac{d_s}{d} \cdot \frac{2e_1}{F_1E_1}$$

For finding calibration relation, the shunt resistance again gives

$$\frac{e_1{}^c}{E_1} = \frac{\delta R}{4(R+R_1)}$$

Which provides the calibration relation

$$\gamma^c = \frac{2cd_s}{l_s d} \cdot \frac{R}{2F(R+R_1)}$$

CHAPTER - 3

EXPERIMENTAL RESULTS AND DISCUSSION

Experiments have been carried out mainly on aluminium material to evaluate its flow stress at high strain acceleration. Tubular specimen were machined from a single piece of commercially available aluminium bars of 25mm dia. Preliminary experiments have been carried out to decide the size of specimen. All the experiments were conducted at room temperature.

Experimental observations involves recording of incident, reflected and transmitted pulse on the oscilloscope as shown in the fig.(3.1). Records of oscilloscope have been plotted on the graph sheet with the help of X-Y plotter. Specimen have been subjected to loading pulse with initial rise time of 50-60 μs and then a ramp which increases the torque by 100% in 225 μs duration. The record of reflected pulse gives shear strain rate . The variation of shear strain rate corresponding to the ramp in the incident pulse is observed to be approximately linear. The slope of shear strain rate increase gives the strain acceleration. To obtain strain, the strain rate of reflected pulse is numerically integrated. The record of the transmitted pulse gives a shear stress.

Experiments have been conducted and their details are given in Table 3.1. A typical relation of shear stress - shear strain is shown in Fig.3.2 to 3.4. The curve is similar in nature, to the one given in Fig.(2.5).The flow stress remains constant in both cases. The phenomena of constant flow shear stress even with increasing strain rate can be explained by the shear stress vs. particle velocity diagram. The input loading pulse can be assumed to be in steps as shown in Fig.(3.0).Initial state of stress in the specimen at the incident side is 1. When

FIG. 20. A TYPICAL RECORD OF PULSES

TABLE -3.1

Exp. No.	Load (Kg.)	Torque (N-m)	Specimen Size		
			Length (mm)	Mean dia (mm)	Thickness (mm)
1.	25	39.2	2.5Ø	12.6	Ø.44
2.	35	54.9	2.38	12.45	Ø.45
3.	35	54.9	2.46	12.36	Ø.5
4.	5Ø	78.4	2.5Ø	12.48	Ø.44
5.	25	39.2	2.48	12.56	Ø.52
6.	35	54.9	2.42	12.43	Ø.51
7.	45	7Ø.6	2.4Ø	12.38	Ø.47
8.	25	39.2	2.48	12.54	Ø.54
9.	45	7Ø.6	2.44	12.45	Ø.47
1Ø.	35	54.6	2.47	12.45	Ø.5Ø
11.	25	39.2	2.56	12.48	Ø.52
12.	45	7Ø.6	2.4Ø	12.45	Ø.57
13.	45	7Ø.6	2.52	12.27	Ø.45

TABLE - 3.2

Exp.No.	Load Kg.	Torque N-m	Flow Stress MPa	Strain $x10^{-5}S^{-2}$
1.	25	39.2	79.4	10.6
2.	35	54.9	84	9.2
3.	35	54.9	80.3	9.5
4.	50	78.4	63.8	16.5
5.	25	39.2	47	9.4
6.	35	54.9	74.1	12.3
7.	45	70.6	60.6	14.3
8.	25	39.2	65.2	7.1
9.	45	70.6	67.5	16.6
10.	35	54.9	67.4	13.7
11.	25	39.2	58.5	7.6
12.	45	70.6	57	15.9
13.	45	70.6	52	16.3

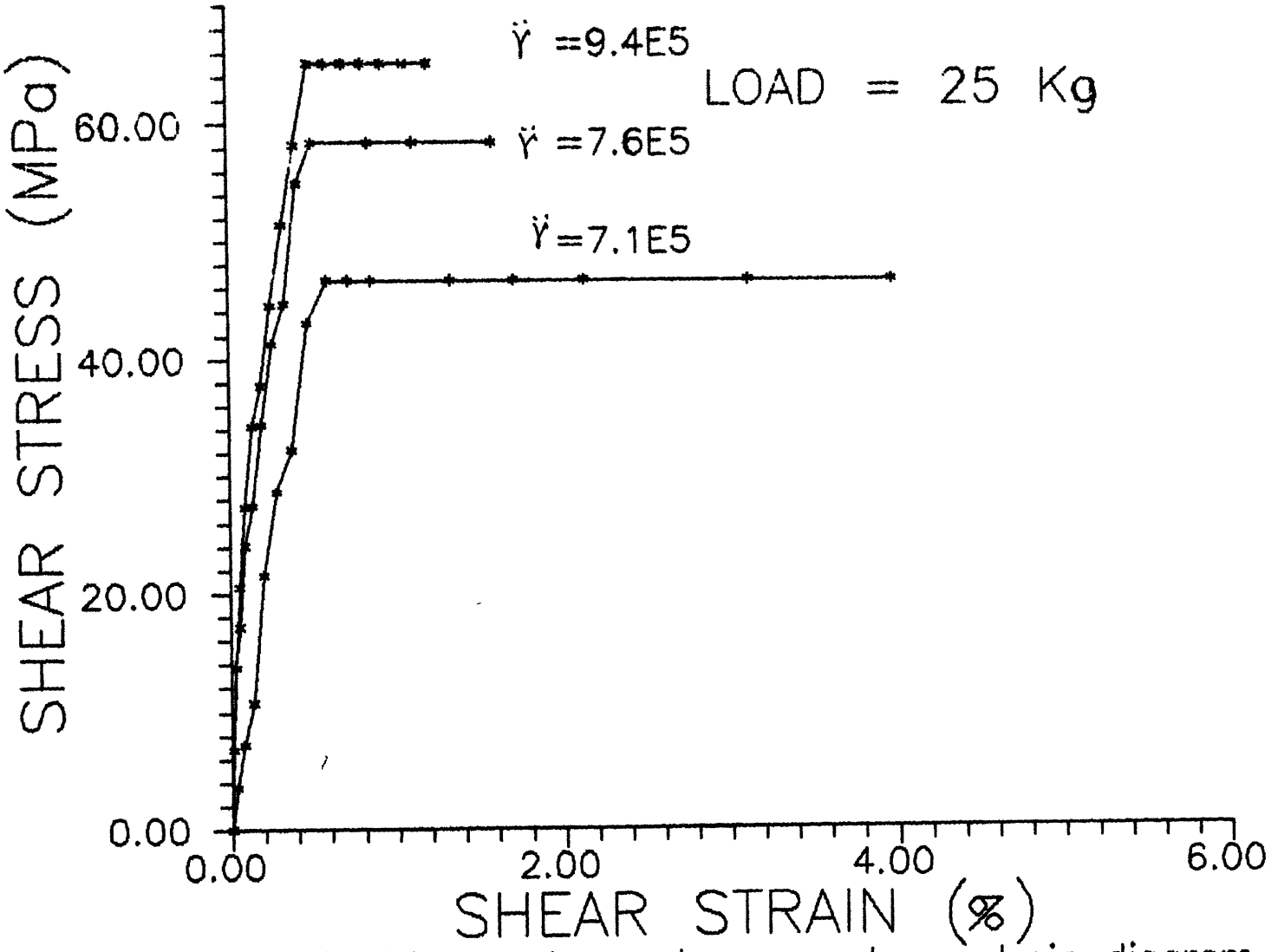


Fig.3.2 shear stress – shear strain diagram.

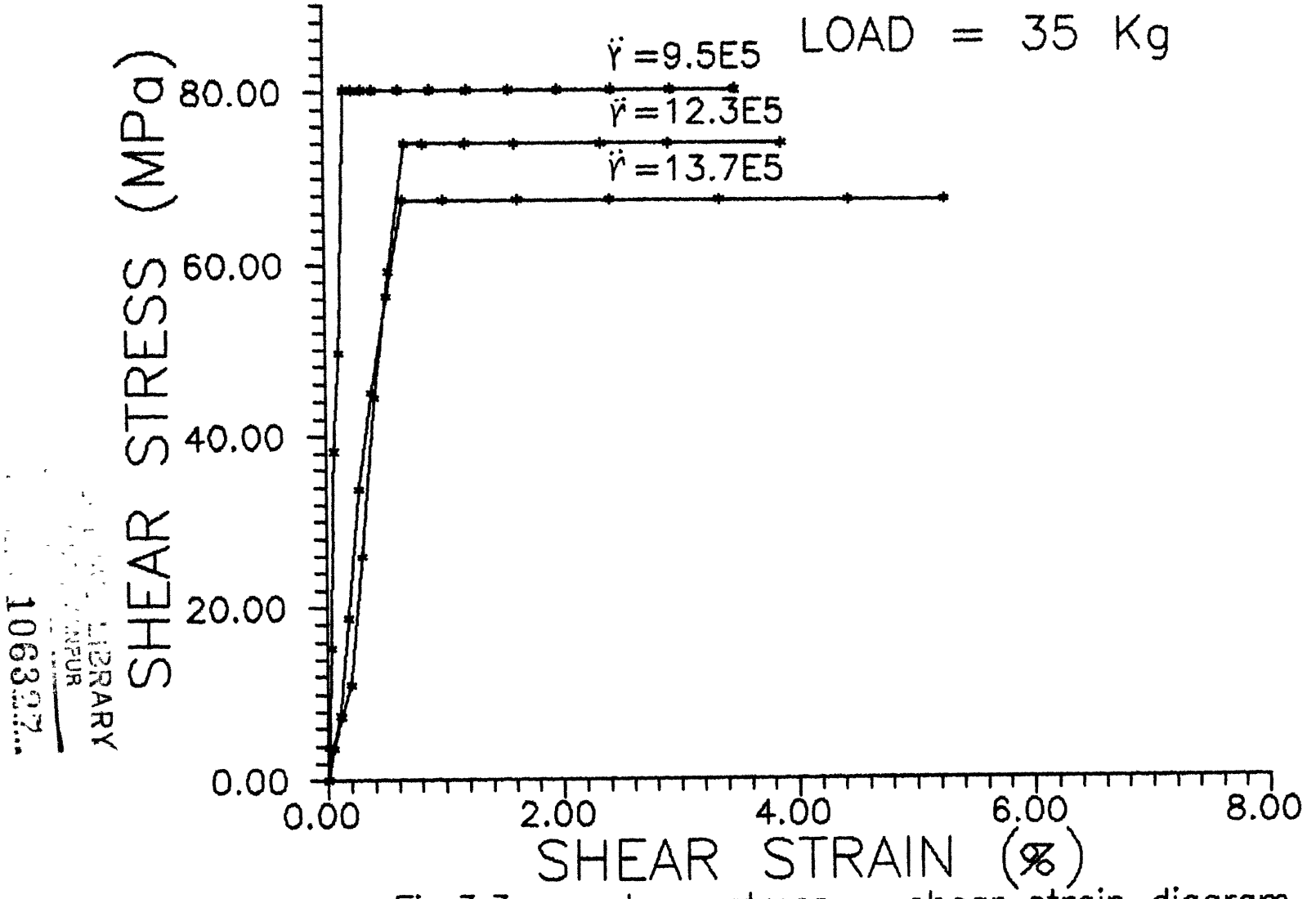


Fig.3.3 shear stress – shear strain diagram.

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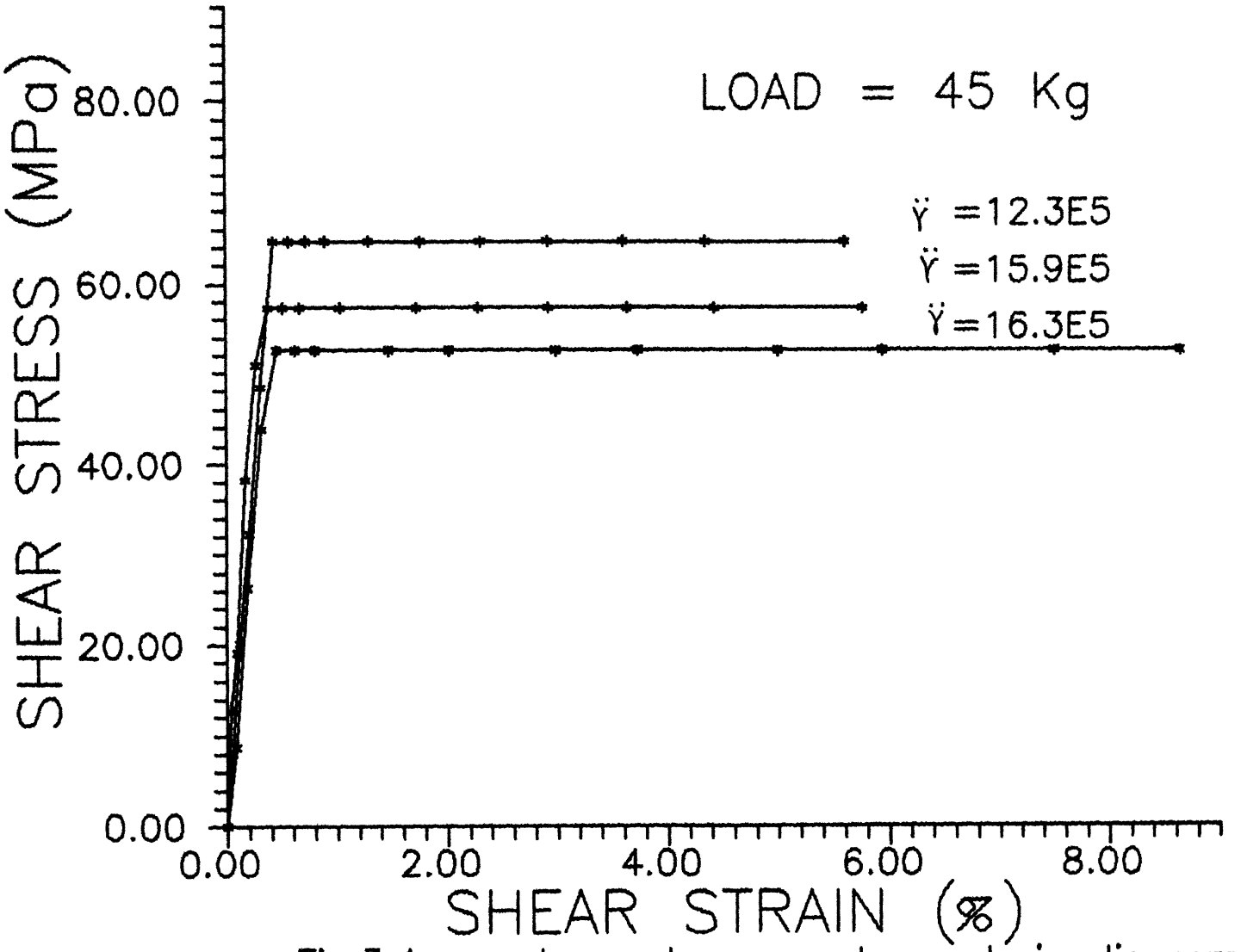


Fig.3.4 shear stress – shear strain diagram.

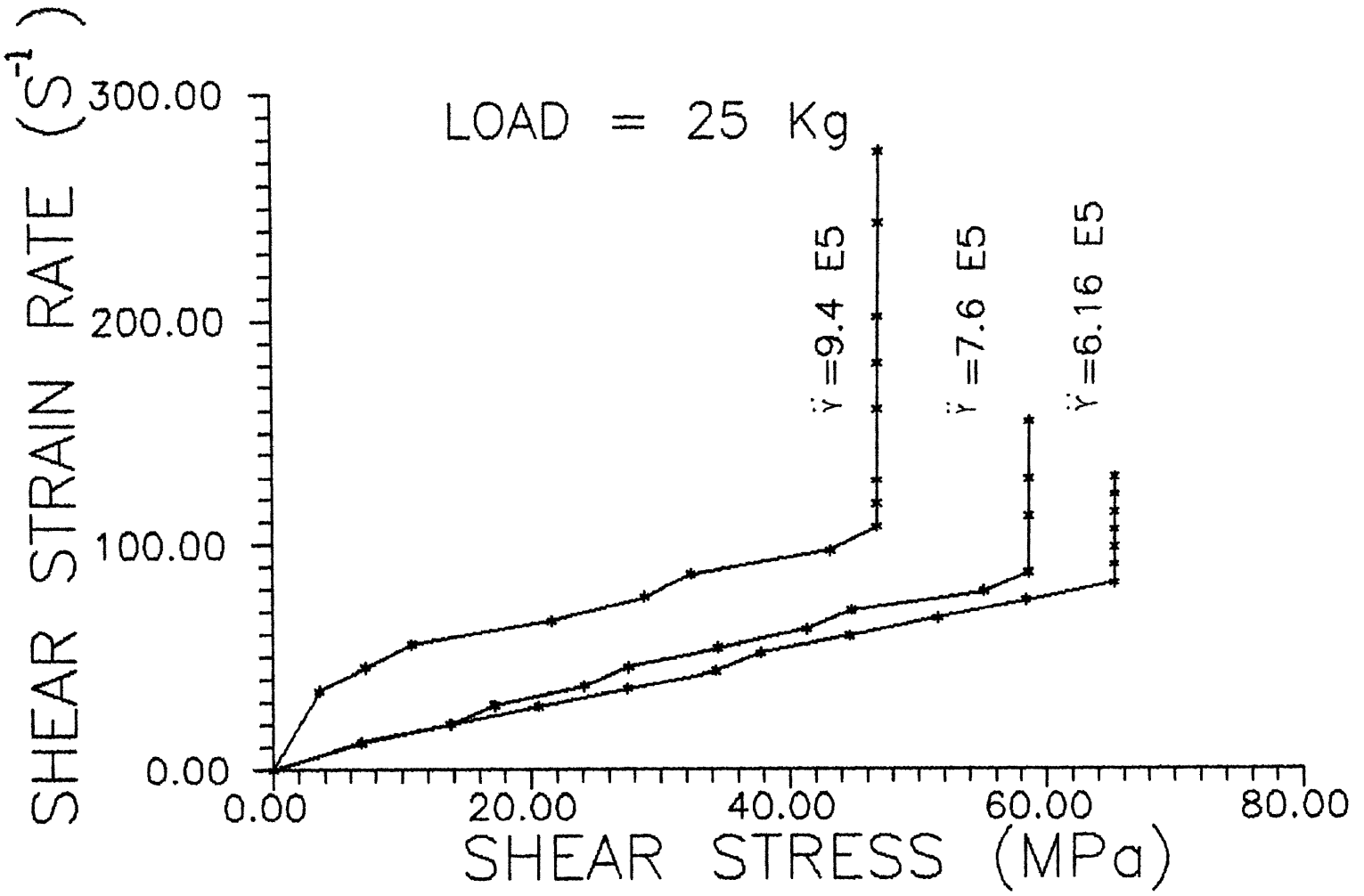


Fig. 3.5 shear stress – shear strain rate diagram.

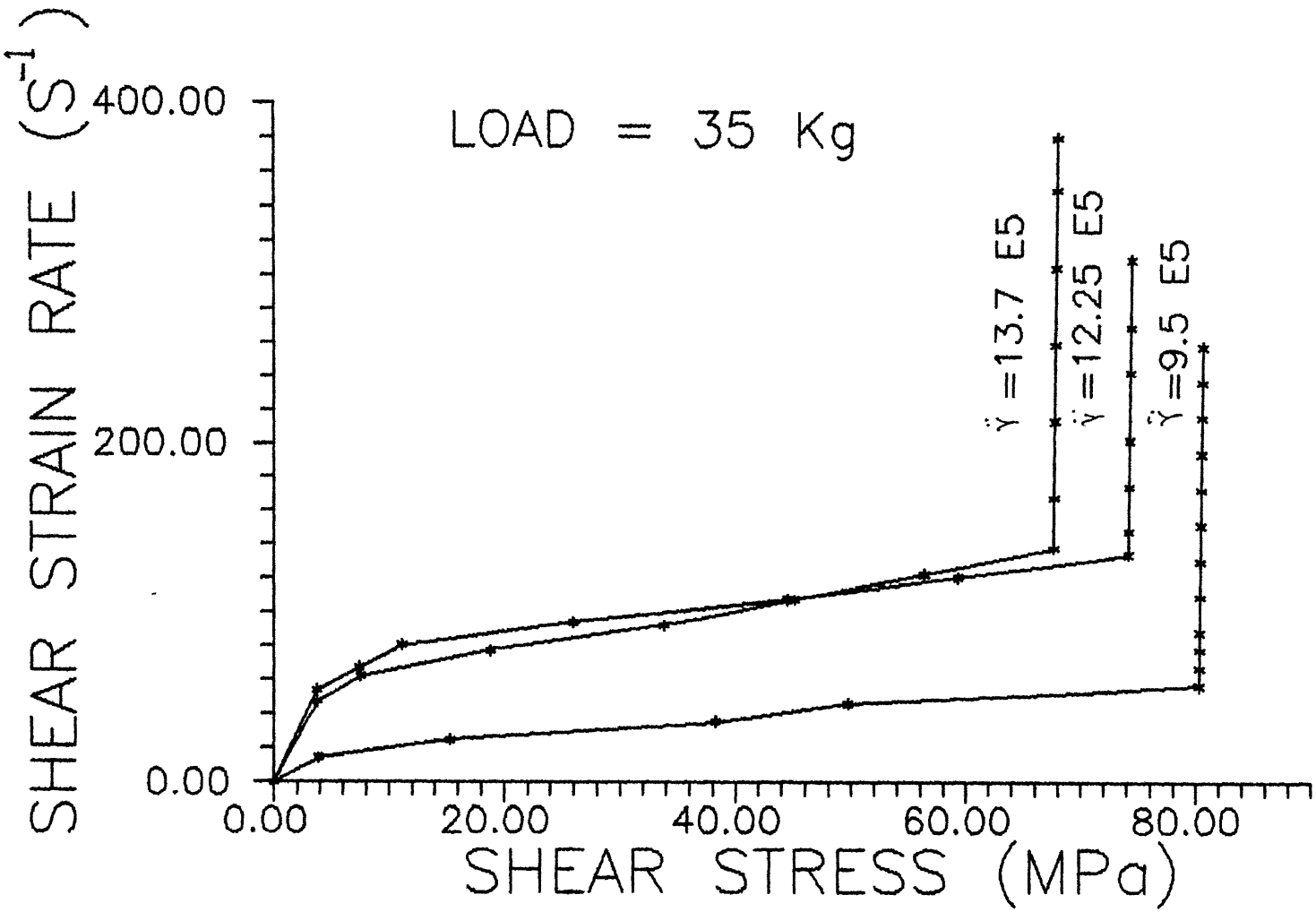


Fig. 3.6 shear stress – shear strain rate diagram.

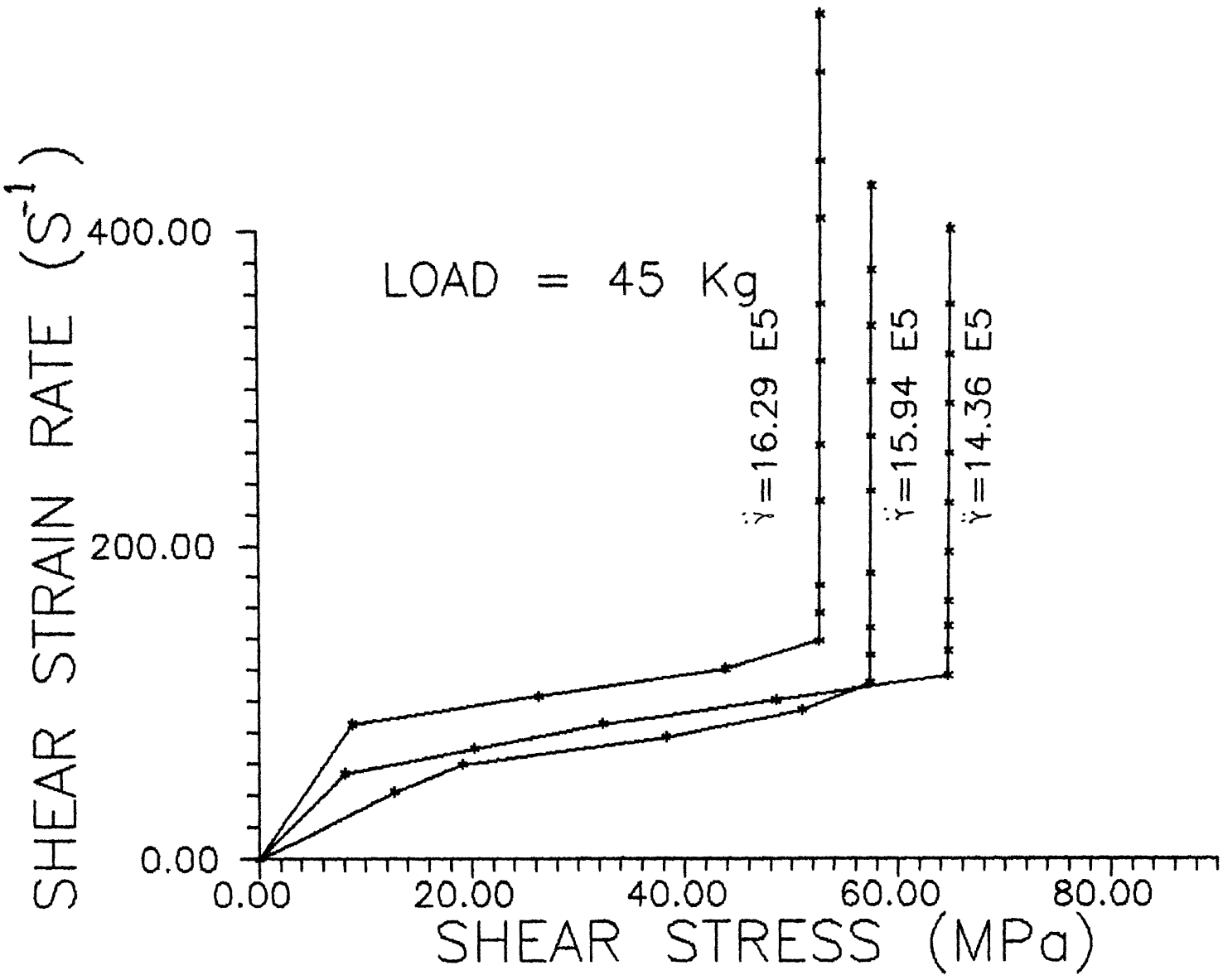


Fig. 3.7 shear stress – shear strain rate diagram.

the pulse reaches at the other end (transmitted bar side) its state of stress becomes 2. As the pulse reflects from this end and goes towards incident bar. The input stress level gone up due to ramp in the loading pulse results in increased particle velocity and hence results in an increase in the value of δv i.e. strain rate. Strain rate as well as stress increases. But as soon as the material is yielded the slope of the stress - strain curve reduces drastically making shear wave velocity in specimen very small. Due to the lack of workhardening in the specimen material of this study,the state of stress in the specimen becomes nearly constant. Any further increase in the loading stress would not increase the flow stress .The particle velocity and hence the strain rate keeps on increasing but stress level remains constant.

Variations of shear strain rate with shear stress are shown in Fig.3.5 to 3.7 for applied loads of 25 Kg,35 Kg and 45 Kg(Torque of 39.2 N-m, 54.9 N-m, 7Ø.6 N-m respectively). Each figure describes three experiments. In these figures the strain rate increases gradually with stress until the specimen attains the state of constant flow stress at a strain acceleration. Since the flow stress does not depend on the strain rate, each experiment provides a relation between the strain acceleration and the flow stress. Table 3.2 lists the relations of all the experiments. They are plotted on Fig.3.8.

The experimental results lie on two different curves. In each curve shear flow stress decreases. The reasons for two curves are not understood.

The decrease in the flow stress with the increasing strain acceleration is clearly evident from the figure. 25% decrease in strain acceleration increases the flow stress by 23%. Although both follow the same trend of decreasing shear flow stress with increasing shear strain acceleration.

The present experimental results are compared with the results obtained by Kumar[8] who conducted experiments on mild steel through machining on a lathe. The graph between shear flow stress and shear strain rate at different shear strain

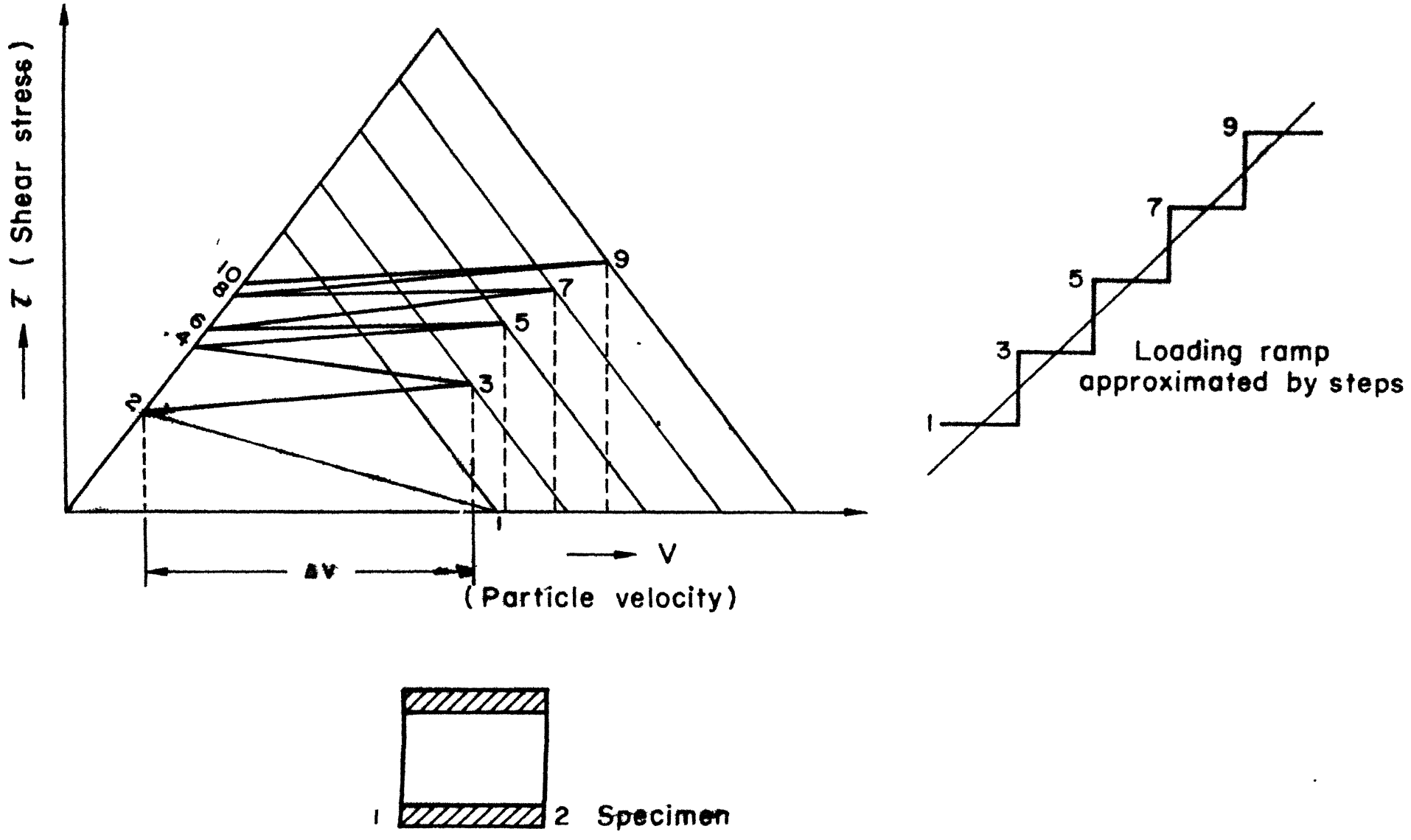


Fig. 3.0 Shear stress - particle velocity diagram for a ramp input pulse

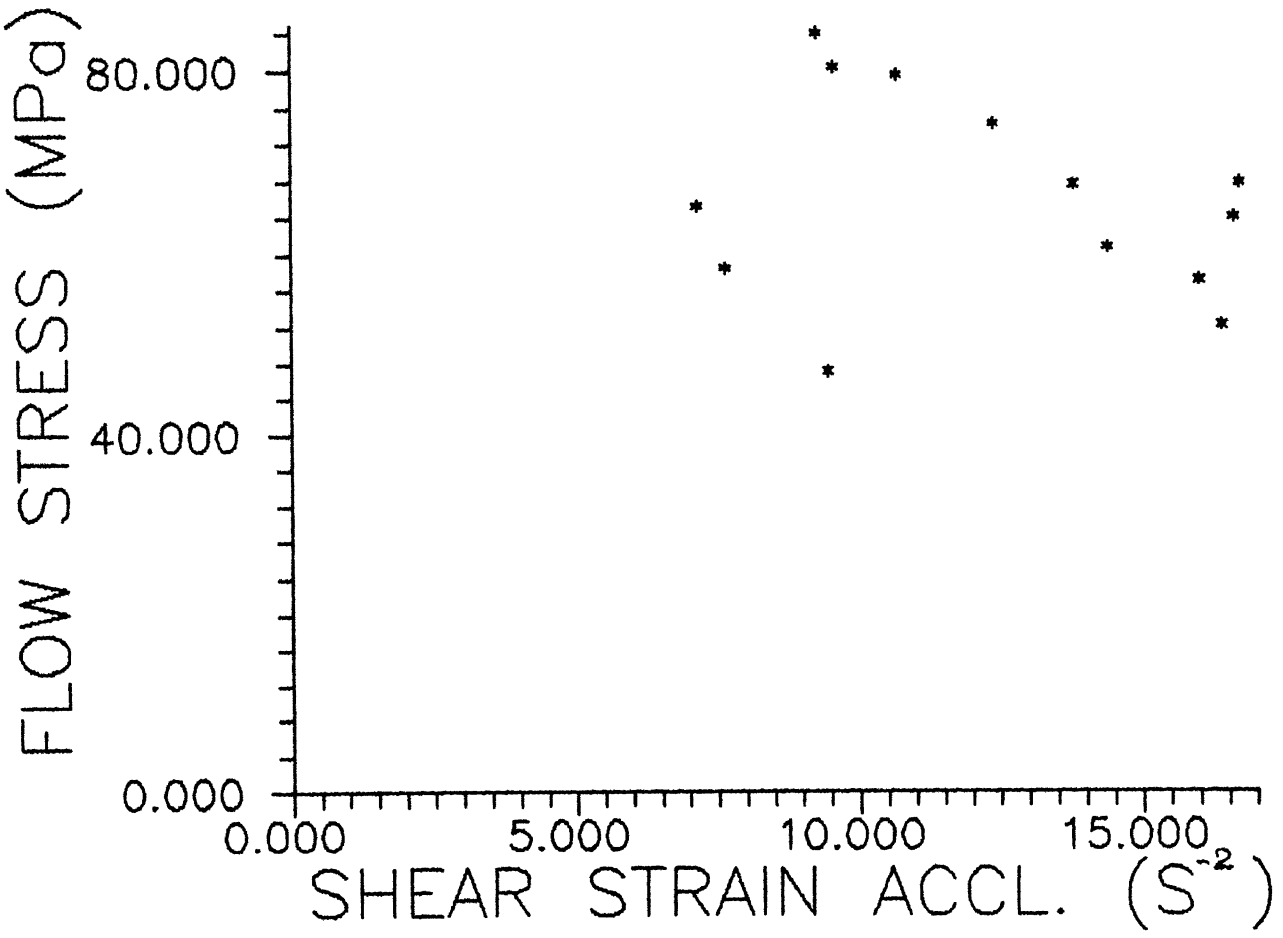


Fig.3.8 Shear strain acceleration – flow stress

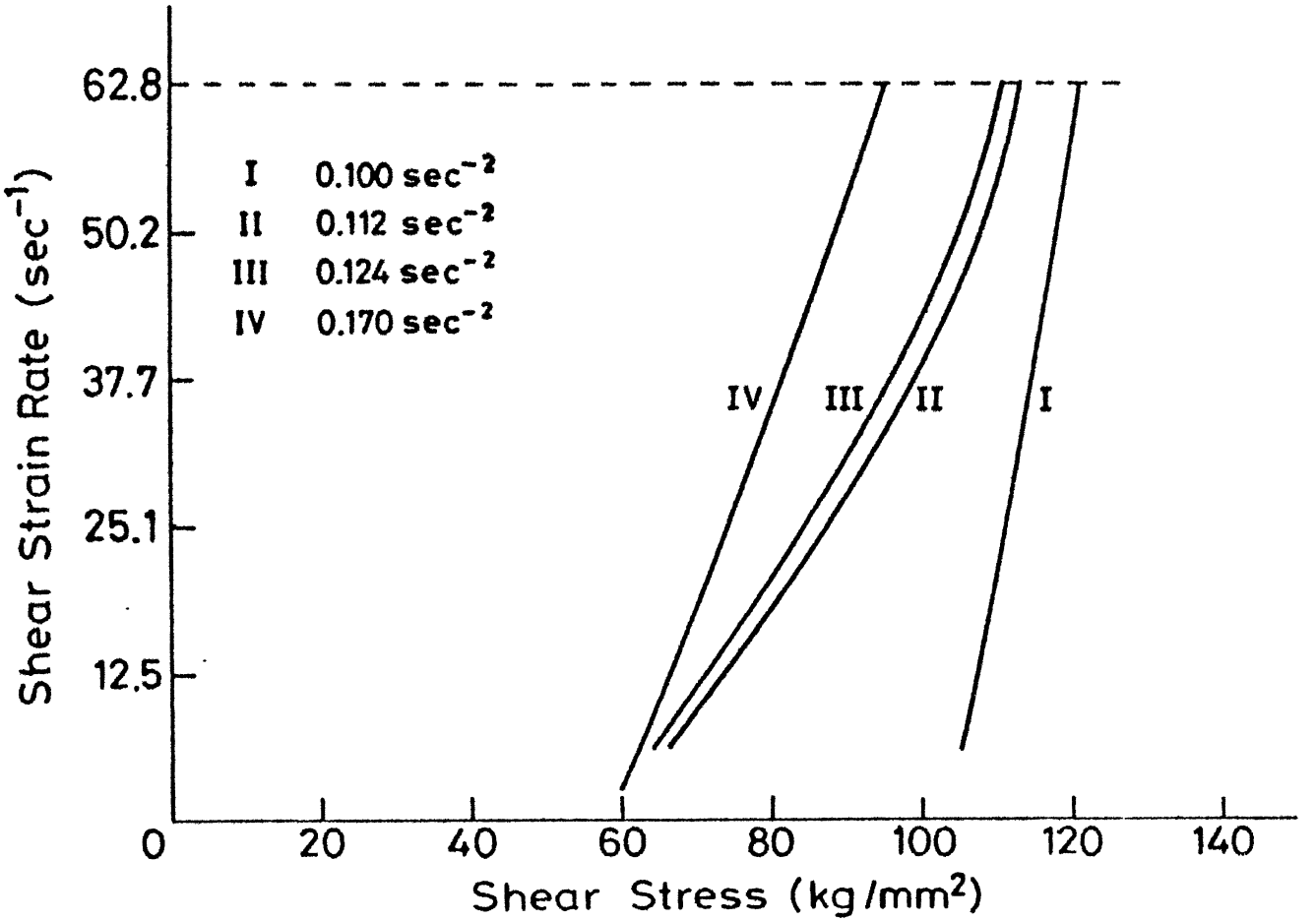


Fig. 3.9 Effect of increasing strain acceleration on shear flow stress.

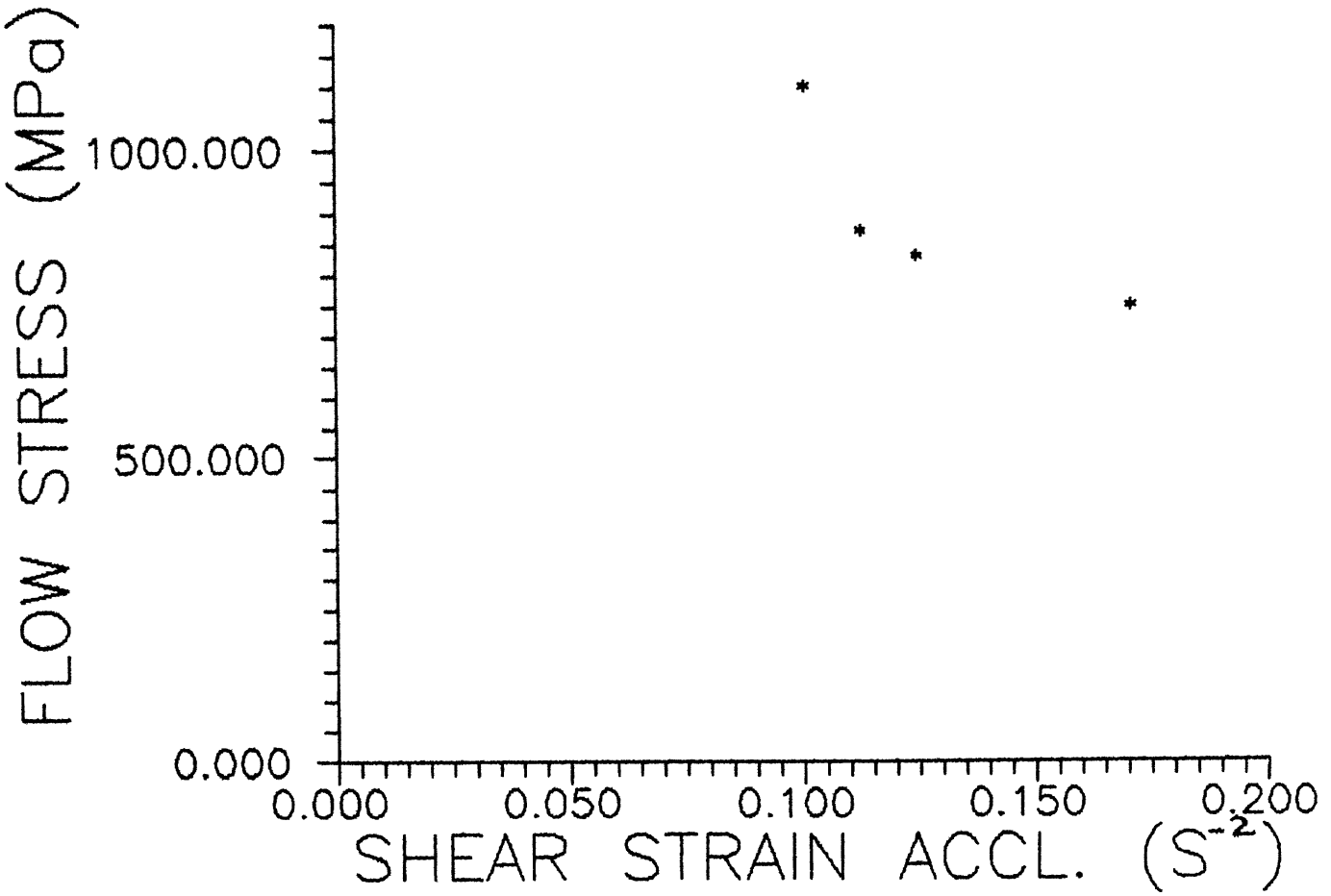


Fig.3.10 shear strain acceleration – flow stress (Ref.8)

acceleration obtained by Kumar is shown in fig.(3.9).This graph indicates that the shear flow stress is affected to some extent by the strain rate whereas in the present work flow stress is unaffected by strain rate. This probably due to presence of strain hardening effect,which is high in the mild steel as compared to that in the aluminium. In Kumar's work, the specimen were subjected to a very low strain acceleration about $1/10^{7}$ times the strain acceleration of the present work. Kumar achieved his strain acceleration through the machining of the taper bar on the lathe which is much slower than the strain acceleration obtained in this study using Kolsky technique. In fact, a high strain rate of about 300 S^{-1} was acquired in a small duration of about 250 μs giving rise to a very high strain acceleration. From Kumar's results , another graph between shear strain acceleration and shear flow stress for a chosen shear strain rate of 25/s is drawn to compare with present result as shown in the fig.(3.10). It is observed both the graph have same trend. A 25% decrease in strain acceleration of Kumar's work results an increase of 32% flow stress -very close to the results of this study.

CHAPTER - 4

CONCLUDING REMARKS

The preliminary objective of setting up an apparatus to produce ramp input pulse to conduct high strain rate shear test at varying strain rate, so that the effect of the shear strain acceleration can be accounted, is successfully met with. The incident bar of the stored torque Kolsky apparatus is modified to a taper between clamp and torque pulley. The proper size of the specimen is decided to suit the ramp loading pulse of approximately 700 μs duration.

Tests have been conducted on commercially available aluminium metal and the effect of shear strain acceleration on flow stress is observed. The flow stress is found to decrease with increasing shear strain acceleration. From experiments it is observed that an increase in shear strain acceleration by 25% results in a decrease of flow stress by 23%.

SUGGESTIONS FOR FURTHER STUDY :

(i) More experiments are needed to conduct the tests at wider range of torques.
(ii) Results on materials of high workhardening should be compared with those of low workhardening.
(iii) The test set-up should be improved to increase the loading rate by using high yield stress incident bar.
(iv) The change in microstructures due to high rate of loading should be studied.

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